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The Preferential Loss of Small Geographically Isolated Wetlands on Prairie Landscapes

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Graduate Program in Geography
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science
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THE PREFERENTIAL LOSS OF SMALL GEOGRAPHICALLY ISOLATED
WETLANDS ON PRAIRIE LANDSCAPES

(Thesis format: Monograph)

by

Jacqueline Noreen Serran

Graduate Program in Geography

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

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Abstract and Keywords

Reliable estimates of wetland loss require improved wetland inventories and effective monitoring programs. To improve upon current wetland inventories, a novel method for mapping wetlands using an automated object-based approach was developed for a regional watershed located in central Alberta. This approach used digital terrain objects derived from Light Detection and Ranging (LiDAR) data for which 130,157 wetlands were identified. Using this LiDAR derived wetland inventory, wetland loss estimates (% number and % area) were obtained by applying a wetland area vs. frequency function to the wetland inventory for the watershed. Using this power law, it was found that historically, there has been a 69.3% number loss and a 9.96% area loss when we accounted for mixed pixels. When we removed any wetland less than the estimated minimum mapping unit (0.02 ha), a 16.17% number and a 2.56% area loss within the watershed was estimated. This wetland loss is a concern as it is concomitant with a loss of ecosystem services.

KEYWORDS: wetland, object-based techniques, area, frequency, Alberta

Co-Authorship Statement

This thesis will be formatted into one manuscript in preparation for submission to an academic journal (to be determined). Jacqueline N. Serran (JNS) will be the first author as she will write the manuscript and contributed to the conceptual design, method development, and data collection and analysis. Dr. Irena F. Creed will be the second author as she contributed to the conceptual design, method development, and interpretation of the data analysis. She also provided the financial resources to complete this research project. This M.Sc. thesis benefitted from a grant called the “Wetland Health Project” which was awarded to IFC by the Alberta Wetland Research Initiative (AWRI), a Natural Science and Engineering Research Council (NSERC) Canada Graduate Scholarship Masters (CGS-M) to JNS, and a Western Graduate Research Scholarship to JNS.

Dedication

*I dedicate this thesis to my supportive and loving parents, Colleen and Donald Serran,
my wonderful sister, Cathleen,*

and last, but not least, my best friend and all-star partner, Adam.

*Thank you for believing in my dreams and providing me with the emotional and financial
support to achieve them.*

Without each of you none of this would have been possible.

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List of Abbreviations

CWI	Canadian Wetland Inventory
DEM	Digital Elevation Model
DUC	Ducks Unlimited Canada
GIWs	Geographically Isolated Wetlands
LANDSAT	Land Satellite
LiDAR	Light Detection and Ranging
MMU	Minimum Mapping Unit
p_{dep}	Probability of Depression
PPR	Prairie Pothole Region
RADAR	Radio Detection and Ranging
RADARSAT	Radio Detection and Ranging Satellite
SPOT	Système pour l'observation de la Terre

Chapter 1: Introduction

1.1 Problem Statement

The Prairie Pothole region (PPR) is a large physiographic region extending from the Prairie Provinces of Canada into the Northern Great Plains of the United States. Due to previous glaciation, the landscape is pockmarked with millions of small depressions that fill with water, creating wetlands. Hydrologically, these wetlands are isolated from surface water networks and larger regional groundwater systems, and they receive the majority of their water inputs from precipitation (Winter & Rosenberry, 1998). Thus, these depressional wetlands are also known as geographically isolated wetlands (GIWs). Due to their isolation, GIWs are often temporary in nature, with many of them holding water for only short periods of time, such as after the spring melt or during deluge (Tiner, 2003). The transient nature and small area of GIWs make them particularly vulnerable to anthropogenic loss and it is perceived that this loss is high in magnitude. The distribution of GIWs is unknown due to a lack of high-resolution wetland inventories (Frohn *et al.*, 2009). Additionally, estimates of loss (or gain) of GIWs is unknown due to lack of monitoring and lack of high resolution wetland inventories. There is a need to develop high resolution wetland mapping techniques that are sensitive to the detection of small GIWs and estimate GIW loss.

1.2 Scientific Justification

1.2.1 The Prairie Pothole Region and Geographically Isolated Wetlands

The PPR is 700,000 km² in area (Guntenspergen *et al.*, 2002) and covers the majority of the prairie eco-zone of North America (van der Valk & Pederson, 2003). Within Canada, the PPR is within four eco-regions: mixed grasslands, moist-mixed grasslands, aspen parkland, and the Boreal transition (Creed *et al.*, 2013). The topography is low in relief and consists of hummocky, knob and kettle formations (Sass *et al.*, 2013). This unique landscape can be attributed to the deposition of glacial till and the forces of melting ice and glacial scouring during the last glacial period (Kantrud *et al.*, 1989). Once the

glaciers retreated, millions of ‘potholes’ were left on the landscape. It is estimated that in Canada there are, on average, 18 potholes per km², but the density can be as high as 90 potholes/km² in some areas (Adams, 1988).

Due to the low permeability of the underlying glacial till and bedrock (Winter & Rosenberry, 1998) potholes fill with water. Usually, potholes are < 1 ha in area and are surrounded completely by upland (Tiner, 2003), making them geographically isolated from the surrounding surface water network (i.e., GIWs) (McLaughlin *et al.*, 2014). GIWs receive the large majority of their water inputs via spring melt and precipitation (Tiner, 2003), with evaporation being the main natural process that causes water loss.

The climate of the PPR is relatively dry, which means GIWs are often not filled with water unless under deluge or immediately after spring melt. Climate oscillations between droughts and deluge are common in the PPR (Duvick & Blasing, 1981), and there exists north-south temperature and east-west precipitation gradients, which contribute to the varying wetland hydrologic characteristics throughout the region (Johnson *et al.*, 2005). The small size and transient nature of the hydrologic regime of GIWs makes them sensitive to changes in the amount of precipitation, evaporation, and discharge, and thus climate change.

1.2.2 Wetland Inventories

Wetland management requires accurate wetland inventories. This information is often not available as current wetland inventories often miss capturing small, geographically isolated wetlands, and therefore are inaccurate (Na *et al.*, 2013). Accurate wetland inventories allow for wetland monitoring, estimating rates of change in wetland number and area, and understanding the spatial and temporal patterns of these changes (Li & Chen, 2005). In addition, inventories provide decision makers with information needed to manage wetlands sustainably (Na *et al.*, 2013). Unfortunately, current wetland inventories are often incomplete, time-consuming to create, non-standardized, and out of date (Baker *et al.*, 2006).

Early methods for the creation of wetland inventories involved visual interpretation of aerial photographs and satellite imagery to delineate wetland boundaries (Hutton & Dincer, 1981). This visual analysis of images was effective at providing wetland location (Johnston & Barson, 1993); however, these methods were labor intensive and prone to human error. To reduce the amount of time required to create wetland inventories manually and to reduce human error, computerized and automated methods were developed. The first computerized and automated wetland mapping methods used low-resolution multispectral imagery such as images from LANDSAT multispectral scanner, LANDSAT thematic mapper, and Système pour l'observation de la Terre (SPOT) (Frohn *et al.*, 2009; Lunetta & Balogh, 1999). Supervised (e.g., the maximum likelihood classifier (e.g., Rebelo *et al.*, 2009)) and unsupervised (e.g., Iterative Self-Organizing Data Analysis Technique (ISODATA) (e.g., Parmuchi *et al.*, 2002)) classifications and clustering techniques were conducted on these images to map and classify wetlands. These classifications group image pixels with similar spectral values and assigns a wetland to each of the spectral groupings (Brady *et al.*, 1999; Ozesmi & Bauer, 2002). As new satellites are being launched, researchers are developing methods to map wetlands using higher resolution images from these satellites. Recent studies have utilized RADAR data (Kushwaha *et al.*, 2000), optical imagery (Li & Chen, 2005), hyperspectral imagery (Harken & Sugumaran, 2005) or a combination of several types of imagery (Gala *et al.*, 2011; Gilmer *et al.*, 1980; Na *et al.*, 2013) to map and classify wetlands.

National wetland datasets exist for both Canada (Canadian Wetland Inventory (CWI)) and the United States (National Wetland Inventory (NWI)). However, the size of the minimum mapping unit for these inventories is about 1 ha for the CWI (Fournier *et al.*, 2007) and range from 0.4 ha to 1.21 ha for the NWI (Martin *et al.*, 2012), depending on where you are located in the United States. With the majority of GIWs being smaller than 1 ha (van der Valk & Pederson, 2003), these inventories do not have the ability to effectively detect and delineate GIWs within the PPR.

Within the Canadian portion of the PPR, there exists a high-resolution wetland inventory that was created by Ducks Unlimited Canada (DUC) (Ducks Unlimited Canada, 2014).

The DUC inventory has a minimum mapping unit of 0.02 ha, but full coverage does not exist for the entire PPR. The DUC inventory was created using aerial photographs with manual delineation of wetland boundaries. The resulting objects were then classified based on the Canadian Wetland Classification System (National Wetlands Working Group, 1997). Although this wetland inventory is a vast improvement over previous wetland inventories, the manual nature of the wetland delineation means that it is not an efficient method to be conducted over large geographic areas.

Automated delineation methods using high-resolution data and remote sensing techniques are being developed to overcome the limitations of manual delineation. Currently, automated wetland inventory methods use multi-spectral (Baker *et al.*, 2006; Frohn *et al.*, 2012), optical (Haas *et al.*, 2009; Li & Chen, 2005), microwave (Allen *et al.*, 2013; Gala *et al.*, 2011; Gala & Melesse, 2012), digital elevation data (Gala & Melesse, 2012; Na *et al.*, 2013), or a combination of these remotely sensed products are being used to map wetlands.

There are several limitations to current automated wetland delineation and classification techniques. Often, the remotely sensed imagery that is used are of low resolution, usually between 10 and 30 metres. These low-resolution data result in mixed pixels and the omission of small wetlands, especially in areas that contain a large amount of small wetlands such as the Prairie Pothole Region of North America (Ozesmi & Bauer, 2002). Additionally, using satellite imagery alone to map wetlands may produce inaccurate results due to spectral similarities between different types of vegetation (Maxa & Bolstad, 2009). Though these classification methods and other wetland mapping techniques have been shown to produce sufficient wetland inventories, the accuracy of delineating wetlands increases when ancillary data is added (Ozesmi & Bauer, 2002). More recent studies have effectively mapped wetlands by incorporating supplementary data such as information about topography and soils (Maxa & Bolstad, 2009; Lang *et al.*, 2012).

One promising data source that can be used to map wetlands is Light Detection and Ranging (LiDAR) elevation data. LiDAR is a remote sensing technology where thousands of pulses of light are emitted towards an object. The sensor calculates the

amount of time it takes for the light to be reflected off incident objects and returned to the sensor (Goodwin *et al.*, 2006). The time is then converted into distance from the sensor and the Earth's surface, which allows for the creation of three-dimensional information about the Earth's surface. LiDAR data have also been found to be effective at delineating wetlands in areas with low relief, as these data are able to detect small depressions (Lang *et al.*, 2010, Lindsay *et al.*, 2004, Lindsay & Creed, 2005). LiDAR is also able to penetrate the tree canopy (Lindsay & Creed, 2005), which is effective for detecting wetlands below tree canopies.

However, LiDAR has several limitations such as the inability to get quality returns off of the surface of open water and the inability to effectively characterize steep slopes such as those on river or lake shorelines (Franklin, 2013). Additionally, LiDAR is sensitive to data capture in urban areas as there are many incident surfaces which light can bounce off of. Fortunately, there are ways to overcome the aforementioned limitations. To overcome the open water limitation, LiDAR can be captured during dry years, or the driest time of the year. Also, the shorelines of lakes and wetlands in the prairie potholes tend to be gently sloping towards the water, making LiDAR an effective data input to be used for wetland mapping in the prairie potholes. There also exists mathematical corrections that can be applied to LiDAR DEMs to account for depth to bottom features with water (e.g., Hladik & Alber, 2012).

Another promising method to map wetlands is object based segmentation. Object based segmentation groups pixels into objects, rather than classifying each individual pixel in an image. Recent studies indicate that object-based classification methods are accurate at delineating wetlands as the segmentation process considers neighboring pixels and is able to develop ecologically meaningful objects that can be used to define wetland regions (Grenier *et al.*, 2007).

By creating accurate automated wetland inventory methods using high-resolution remote sensing data that are sensitive to the detection of depressions, we are able to map GIWs quickly, over large geographic areas, using a standardized method. This allows us to obtain a better understanding of the distribution, location, and abundance of GIWs and

hydrologically-connected wetlands within the PPR. This knowledge is needed to inform effective wetland monitoring programs and management strategies.

1.2.3 Wetland Loss

Wetlands provide important functions and benefits; however, these important ecosystems are vulnerable to loss due to anthropogenic development (Davidson, 2014). It is estimated that in some areas of Canada, up to 70% of wetlands have been lost or degraded (Warner & Asada, 2005). These wetland losses are attributed to increasing urban and agricultural development pressures causing wetlands to be dredged and drained for the purposes of economic expansion. However, these estimates are believed to underestimate current wetland loss as almost ten years have passed since the estimates were calculated. Additionally, the wetland inventories used to estimate this wetland loss were coarse in resolution and did not capture the full extent of the GIWs in the PPR. When these wetlands are lost, associated functions are lost as well (McLaughlin & Cohen, 2013). Wetlands need to be managed effectively in a manner that balances the need for economic development and the preservation of wetlands.

A major problem contributing to the lack of information on the true magnitude of wetland loss is the lack of accurate wetland inventories. In many cases, current wetland inventories are too coarse in resolution to be useful in the prairie pothole region (Clare & Creed, 2013; Davidson, 2014; Finlayson *et al.*, 1999). As stated earlier, the National Wetland Inventory for the United States has a minimum mapping unit target of approximately 0.4 to 1.2 hectares (Martin *et al.*, 2012), depending on where you are located in the country. This is particularly problematic as many GIWs, especially those in the PPR, are smaller than 1 ha in size (Tiner, 2003). It is difficult to effectively manage and obtain estimates of the loss of small wetlands when their location is unknown.

Another problem is the preferential loss of GIWs compared to other wetland types in the PPR (Miller *et al.*, 2009). The preferential loss of GIWs can be attributed to the hydroperiod of these wetlands. GIWs, due to their transient hydrologic nature, are relatively easy to remove from the landscape in comparison to more permanent wetlands.

Furthermore, the small and shallow nature of these wetlands allows for conversion of wetlands to agriculture (Galatowitsch, & van der Valk, 1996).

Yet another problem is the lack of wetland monitoring and assessment programs. Comparing wetland loss estimates is often difficult as current methods are non-standardized, with each method having a different definition of what constitutes wetland loss (Dahl & Watmough, 2007). Many of the current wetland estimates are created using historical aerial photographs or transect studies to estimate wetland loss, which can be time consuming and prone to error (Davidson, 2014). Despite these challenges, information about wetland loss is needed as it allows decision makers to direct conservation efforts to areas that have lost a large number or area of wetlands.

Wetland loss is particularly problematic as it is associated with loss of wetland functions and their resulting beneficial ecosystem services (Naugle *et al.* 2001; Robinson, 1995; Tiner, 2003). A common misconception about GIWs is that the lack of connectivity to the surface water indicates these wetlands function less efficiently than more permanent wetlands and therefore provide fewer ecosystem services (e.g., McLaughlin *et al.*, 2014; Semlitsch & Bodie, 1998). Though GIWs are completely disconnected from the surface water network, they have been found to have important contributions to the groundwater system via wetland-groundwater interactions and can be groundwater sinks or sources (McLaughlin *et al.*, 2014; Tiner, 2003; Winter & Rosenberry, 1998). In addition, GIWs are considered important biogeochemical reactors within watersheds as they remove nutrients such as nitrogen (Ligi *et al.*, 2013, Wolf *et al.*, 2013) and phosphorus (Craft & Casey, 2000; Dunne *et al.*, 2007; Reddy *et al.*, 1999) and sequester carbon (Badiou *et al.*, 2011) at rates comparable or higher than connected wetlands. These important functions provide ecosystem services such as the desynchronization and attenuation of flood waters due to the ability of GIWs to retain water so that it does not enter the surface water network (Lane & D'Amico, 2010), and the improvement of downstream water quality (Pomeroy *et al.*, 2014).

1.3 Thesis Objectives and Hypotheses

The first objective of this thesis is to develop a novel method for mapping wetlands that is particularly sensitive to mapping the small (< 1 ha) GIWs that dominate the Prairie Pothole landscape. These small wetlands are often missed in current wetland inventories due to low-resolution input data. The resulting wetland inventory will allow for the better management of GIWs and for the better understanding and documentation of wetland losses.

The second objective of this thesis is to explore the magnitude of wetland loss within a regional watershed in Alberta. A lost wetland is defined as a wetland that has been drained or removed from the landscape for development purposes. The loss estimates will be made by applying a power law wetland area vs. frequency function to the LiDAR derived wetland inventory, which was produced as a result of the first objective. We hypothesize that there has been a high percent number and percent area loss within the watershed.

To meet our objectives and test the hypotheses, we will complete the following tasks for the Beaverhill watershed ($\sim 4500 \text{ km}^2$) in Alberta, Canada:

1. Develop an automated object-based wetland mapping technique by applying object-based segmentation to Light Detection and Ranging (LiDAR) digital elevation data; and
2. Determine the historic loss (or gain) of wetland number and area for the Beaverhill watershed using the LiDAR-derived wetland inventory created in the first task.

1.4 Thesis Organization

This thesis is in a monograph format. The first chapter provides an introduction to the thesis and literature review, including a statement of the problem, scientific justification for conducting the research, and the thesis objectives. Chapter 2 discusses the materials and methods used to map wetlands and estimate wetland loss. The third chapter describes the major findings and results of the wetland mapping process and the wetland

loss estimates for the Beaverhill subwatershed in central Alberta. Chapter 4 discusses the results and places them within current and historical scientific literature. Chapter 5 provides the overall conclusions for the thesis and outlines future work that will be conducted. Appendices are provided at the end of the dissertation, and are not central to the thesis, but provide further information about the methods used and analysis that was not included in the thesis.

Chapter 2: Methods and Materials

2.1 Test Area

The Beaverhill watershed (4,500 km²) is located in central Alberta and covers a portion of the Prairie Pothole Region of North America (Figure 2.1). The climate is continental, with an average annual temperature of 2.6°C characterized by warm summers and cold winters and a total average annual precipitation of 446.1 mm, with the majority of the precipitation falling during the growing season, according to the Canadian Climate normals for the 30-year period from 1981-2010 (Environment Canada, 2010) (Figure 2.2). The landscape is rolling, hummocky terrain that was created due to glaciation. Elevation within the watershed ranges from 586 to 812 m above sea level. The landscape is pockmarked with a large number of depressions that fill up with water either temporarily in the spring or have a surface water connection with allows them to contain water permanently all year round.

The study area is situated in the Parkland and Boreal natural regions of Alberta (Young *et al.*, 2006). The Cooking Lake Moraine covers the majority of the central portion of the study area and is characterized by a mixture of forests, grasslands, and wetlands. The natural vegetation is characteristic of the Parkland natural region of Alberta and the Central Parkland and the Central Mixwood natural sub-regions of Alberta (Natural Regions Committee, 2006). These natural regions contain a mixture of aspen and prairie vegetation dominated by plains rough fescue and aspen trees (Natural Regions Committee, 2006). The centre of the watershed is extensively forested with mixed-wood Boreal forest (Young *et al.*, 2006). A large portion of the moraine has been designated as either national or provincial parks or protected areas, including Elk Island National Park and Beaverhill Lake (a RAMSAR site). Soil types within the study area include primarily Black Chernozemic, Black Solonetzic, and Orthic Grey Luvisols and the bedrock is composed of sandstone, siltstone, mudstone, shale, and ironstone beds (Howitt, 1988). This diverse mix of land use and land cover allows for the testing and exploration of the robustness of our wetland mapping method.

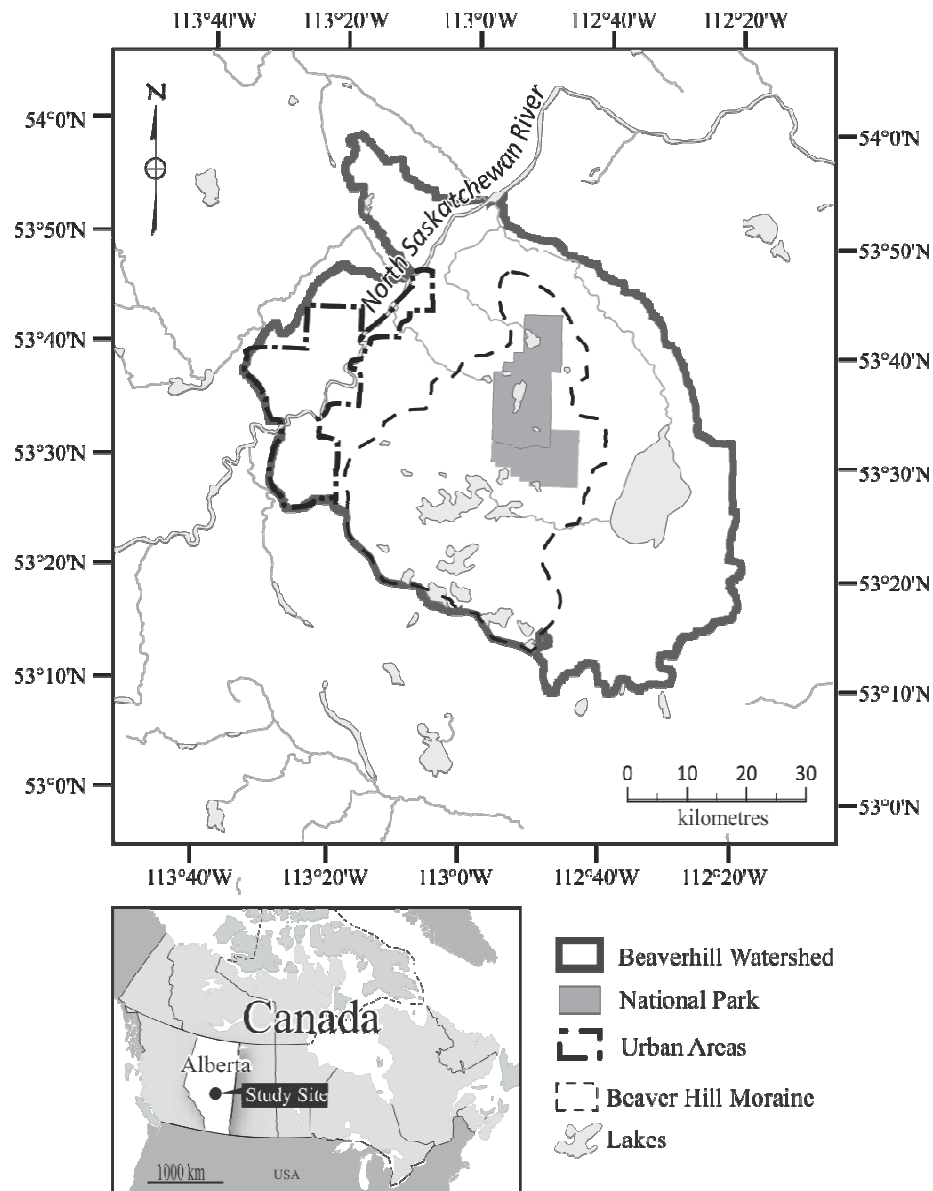


Figure 2.1: Map showing the location of the study watershed, the Beaverhill watershed, Alberta, Canada. The watershed is located in Central Alberta and encompasses the Eastern portion of the City of Edmonton. The Cooking Lake moraine is located in the centre of the watershed and includes Elk Island National Park.

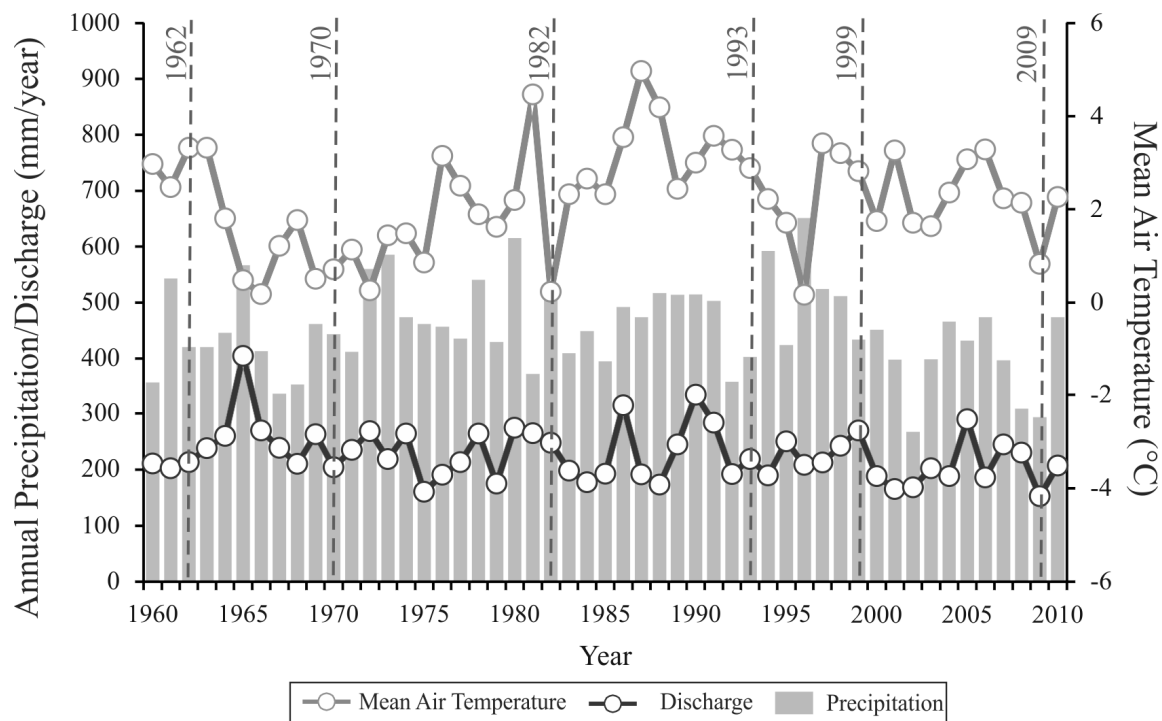


Figure 2.2: The cumulative mean monthly discharge, total annual precipitation, and mean average temperature for the time period of 1960-2010 for Edmonton International Airport. The years used to derive the water permanence information are indicated in grey dashed lines.

Additionally, the land uses within the watershed are representative of the developed “white zone” of Alberta, ranging from urban to agricultural (predominantly grassland and pastureland) to natural forests. Development pressures within the watershed have been primarily attributed to the conversion of land to cattle pasture and croplands (Young *et al.*, 2006). Urban expansion has occurred around the city of Edmonton and Strathcona County, but the rate of expansion is estimated to be slower than the expansion experienced in other areas of Southern Alberta (e.g., Calgary) (Clare & Creed, 2013). The Edmonton Census Metropolitan Area has expanded by an estimated 10.4% from 2000 – 2007. Future urban land use change is expected to occur within the watershed as the City of Edmonton is projected to expand at an estimated rate of 1.3%/year from 2006 until 2041 (Government of Alberta, 2007).

2.2 Wetland Inventory

2.2.1 Manually Delineated Reference Wetlands

We used the best available wetland inventory for the study region - the high-resolution Canadian Wetland Inventory (CWI) created by Ducks Unlimited Canada to develop thresholds to be used in our method (calibrate) and determine how effective these thresholds are (validate) for use in our method. A flow chart of the method to create the reference data is shown in Figure 2.3. Professionals trained in photogrammetry created the high-resolution wetland inventory using stereo-pairs derived from 1:20,000 aerial photographs that were captured in 2007. Original negatives of the images were scanned on a photogrammetric scanner to increase the pixel resolution to 25 centimeters. Stereo models were then created using existing ground control points and elevation data obtained from an enhanced digital elevation model. To delineate wetland boundaries, stereo interpretation was used to identify topographic and vegetative indicators of a wetland’s presence and using this information, the boundaries of the wetlands were captured manually. The minimum mapping unit of this high resolution wetland inventory is 0.02 hectares (ha) and wetland features and attributes were collected in concordance with the National Wetlands Data Model (Natural Resources Canada, 2010).

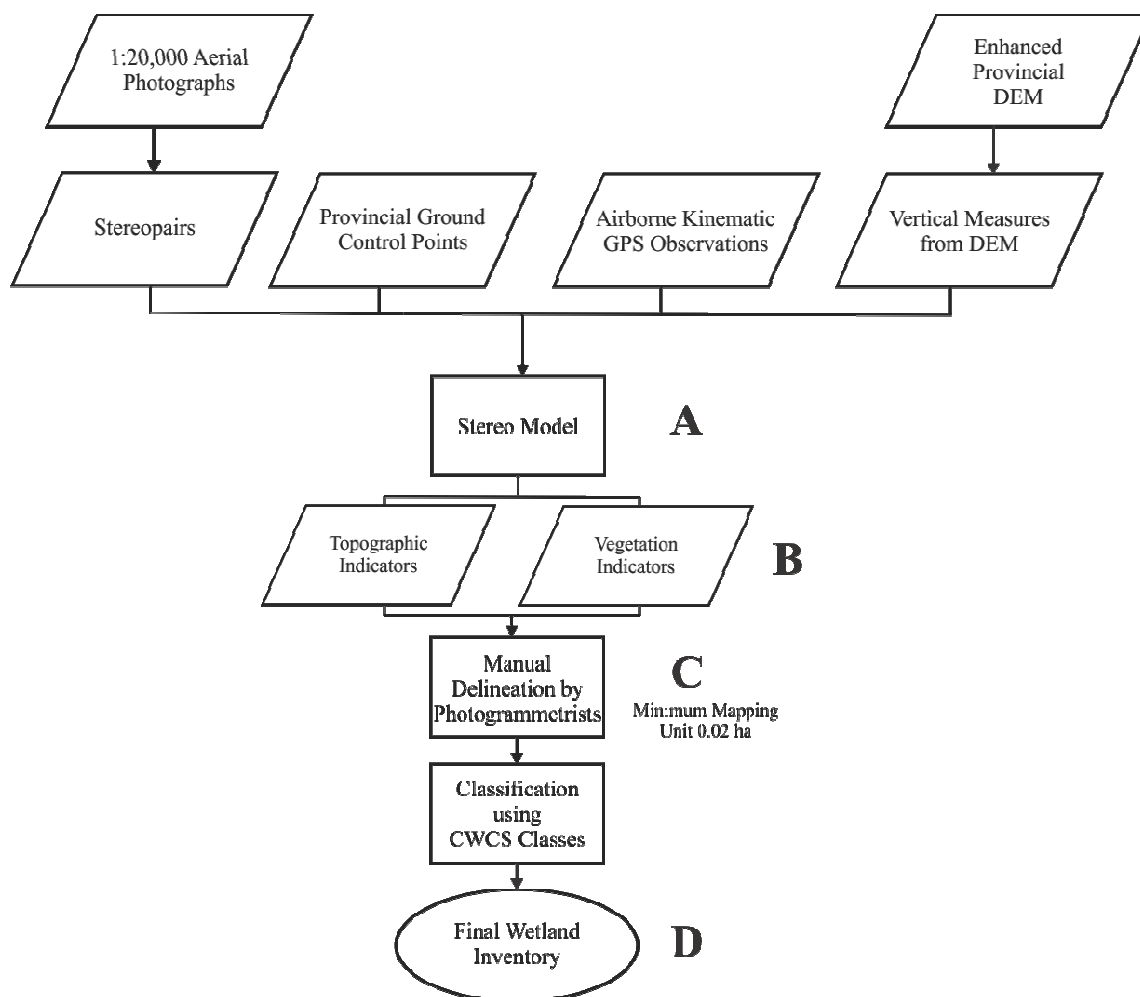


Figure 2.3: Flow chart showing steps used for the manually derived high-resolution portion of the Canadian Wetland Inventory that was used as the reference data. A, B, C, and D designations indicate steps that are comparable to those with the same letter in Figure 2.4, which describes the automated object-based wetland inventory using terrain objects.

We processed the reference wetland inventory to meet the needs of our study by dissolving wetland boundaries and removing those wetlands that were classified as dugouts or human made features as the goal was to map natural wetlands. Dissolving wetland boundaries was done as wetlands within the CWI may consist of several internal polygons that needed to be combined together to delineate the outer boundary of the wetland. The CWI is suitable for validation of the wetland mapping method as it is high-resolution, standardized, covers a large portion of the study area, and was created within two years of the LiDAR data capture. Information about the data layers used in this paper, including their data source and data source years can be found in Table 2.1.

2.2.2 Automatically Delineated Wetlands – Objects

We used a LiDAR digital elevation model (DEM) with a horizontal resolution of 3 meters (m), point spacing of 0.75 m, and an estimated vertical accuracy of ~15 centimeters (cm) to develop a probability of depression layer which forms the foundation of the wetland mapping technique (Figure 2.4). LiDAR data are typically captured via a sensor on an airplane which measures the amount of time it takes for a laser light emitted towards an object to return to the sensor (Hogg & Holland, 2008). The length of time it takes for the reflection of the laser to reach the target is then analyzed by the sensor and translated into a distance measurement between the object and the collection instrument. The sensor records several returns as the laser reflects off of incident surfaces such as leaves, tree branches, buildings, and eventually the ground surface (Lindsay *et al.*, 2004). Thus, the last return recorded by the sensor is typically the coincident with the ground's surface, and the first return is typically coincident with the top of tree canopies, or buildings. The LiDAR data for the watershed were collected for a majority of the study area in 2009, with missing areas filled in with data captured in 2007 or 2008 LiDAR data. The LiDAR DEM had a spatial resolution of 3 m and an average vertical accuracy of 15 cm and was georeferenced to the study area. Using this LiDAR information, a bare earth digital elevation model (DEM), which is a model of the ground elevation, was created by using the last returns of the LiDAR data.

Table 2.1: List of data layers used in this project, including their resolution, minimum resolvable unit, time of capture, and source. Where the minimum resolvable unit was not provided we calculated it using the method by Tobler (1987).

Data Layer	Resolution	MMU	Source Data Years	Source
Average Annual Precipitation -Potential Evapotranspiration (P-PET)	1000 m	100 ha	1971-2000	Canadian Forest Service
Bedrock Geology	1:1,000,000	100 ha	1939	Alberta Geological Survey
Surficial Geology	1:1,000,000	100 ha	1960	Alberta Geological Survey
Land Use	5 m	0.0025 ha	2009	Derived from SPOT Imagery
Digital Elevation Model	3m	0.0009 ha	2009	Airborne Imaging Inc.
Canadian Wetland Inventory	1:20,000	0.02 ha	1998 & 2007	Ducks Unlimited
Wetland Permanence	1 m	0.0001 ha	1962 - 2009	Derived from historical aerial photographs

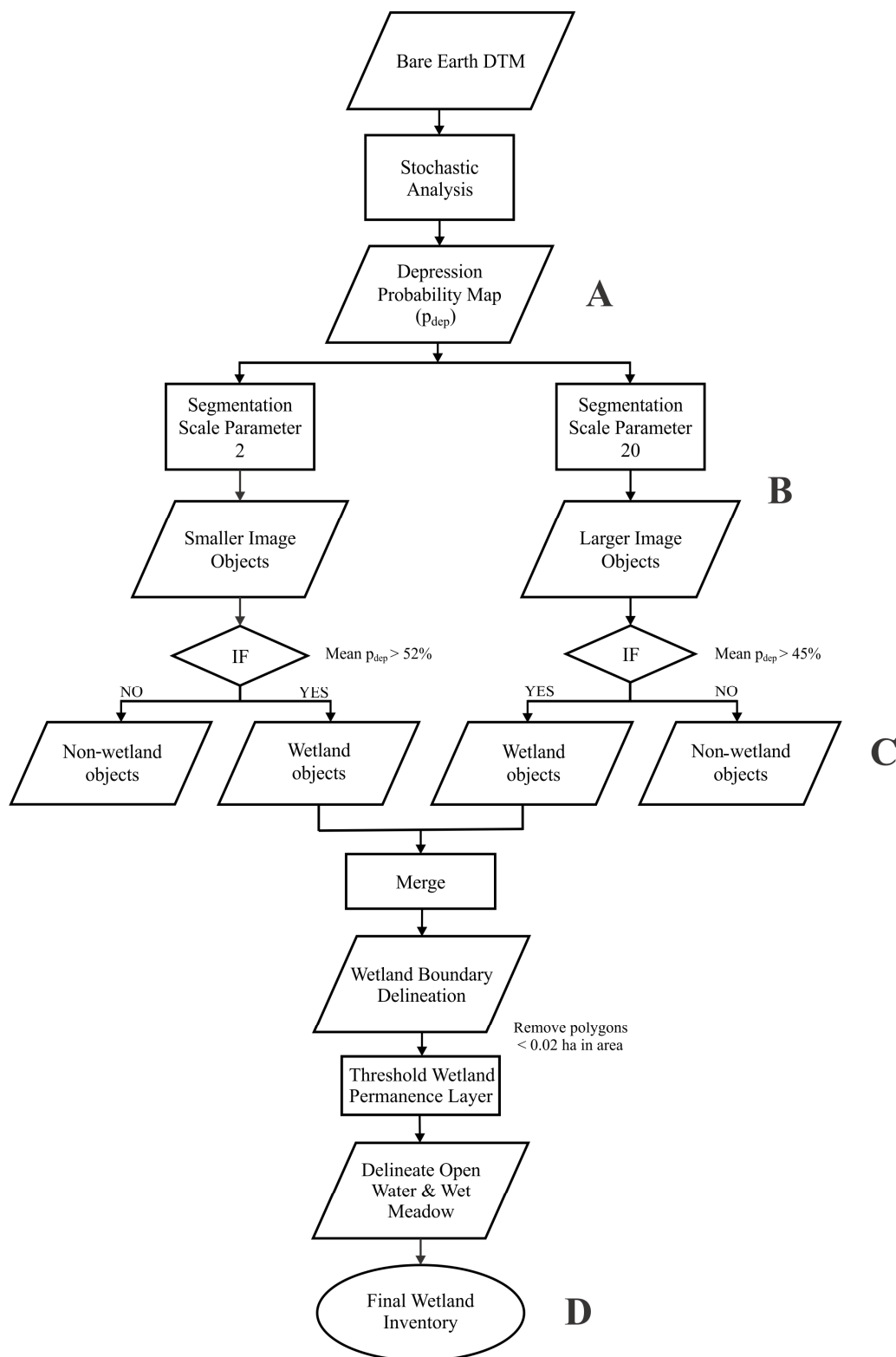


Figure 2.4: Flow chart of steps used for the automated object-based wetland inventory using terrain objects. See Figure 2.3 caption for description of A, B, C, and D designations.

A strong association exists between depressions on the landscape, defined as low lying areas that are completely surrounded by higher elevation, and wetland occurrence (e.g., Creed *et al.*, 2003). The method to map wetlands is based on creating a probability of depression (p_{dep}) layer using a Monte Carlo simulation approach conducted on the LiDAR bare earth digital elevation model (Lindsay *et al.*, 2004). Monte Carlo simulations use repeated random sampling to obtain numerical results to gain insight into an unknown probabilistic entity (Metropolis & Ulam, 1949). The goal of this process is to determine the probability of a depression existing on the landscape by utilizing the digital elevation model's error terms. By using the digital elevation model's error terms, the Monte Carlo simulation process is able to determine where actual depressions exist and where there may be artefacts in the elevation model (Lindsay & Creed, 2006). The p_{dep} layer was generated by adding random elevation errors with a standard deviation of 0.15 m (the vertical accuracy of the LiDAR data) iteratively to the LiDAR elevation model (Creed & Beall, 2009). The elevation-added DEM was then depression filled using the Wang and Liu (2006) algorithm, and modified cells after the DEM filling are identified and recorded. This process is repeated until the root mean square difference between two realizations is less than 0.001 (Lindsay *et al.*, 2004) and the probability of depression is calculated by the number of times a cell was included in a depression and filled. A value of 0 in the p_{dep} layer means that the cell was not included in a depression during any of the simulations and therefore has no probability of depression; and a value of 1 indicates the cell was included in a depression and filled every simulation that was run and has a 100% probability of being a depression (Creed & Beall, 2009).

Though the p_{dep} layer has been used to map wetlands before, past studies have applied a threshold to the p_{dep} layer to map wetlands (e.g., Creed & Beall, 2009). The wetland mapping method in this study applies object-based segmentation to the p_{dep} layer to map wetlands. The resulting p_{dep} layer was segmented into image objects following the multi-resolution segmentation algorithm (Baatz & Schäpe, 2000). The multi-resolution segmentation algorithm begins with one pixel and merges the single pixel objects with surrounding regions based on a pair-wise clustering process (Carleer & Wolff, 2006). The pair-wise clustering process aims to merge regions with similar color, smoothness, compactness, and spatial criteria to create relatively homogeneous image objects (Aldred

& Wang, 2011; Carleer & Wolff, 2006). User-specified segmentation parameters of layer weights, compactness, shape, and scale parameters help to achieve the desired segmentation. By conducting object based segmentation on the probability of depression layer, we are able to increase the convolution of the edges of wetland objects in comparison to other inventories, which is particularly important when using wetland inventories to estimate wetland function. Indicators of wetland function such as the perimeter-to-area ratio (Van Meter & Basu, 2014) rely on inventories that detect edge convolutedness. Though the elevation model that was used in this study was high resolution, the capturing of edge convolutedness is particularly advantageous when using coarser digital elevation models which have a higher number of mixed pixels.

The use of object-based segmentation is also advantageous for landscapes with a broad range of wetland sizes as segments of different resolutions are allowed enabling detection of both small, isolated wetlands and larger, surface water connected wetlands. For the wetland mapping segmentation procedure, we used a larger scale parameter of 20 and a smaller scale parameter of 2. The scale parameter is a unitless value that determines the maximum possible change in heterogeneity that can be caused by merging neighboring image segments into one segment (Ikokou & Smit, 2013). The lower the threshold, the lower the possible change in heterogeneity and thus the smaller the image segment. The scale parameter of 20 produces larger image objects, which effectively maps larger wetlands. The larger scale parameter was required as the smaller scale parameter terrain objects, when classified, were found to miss portions of larger wetlands due to the variation in mean terrain object p_{dep} values within wetlands. The scale parameter of 2 is typically smaller than what is used in existing wetland studies (Moffett & Gorelick, 2013; Reif *et al.*, 2009), but it was deemed as appropriate for use in this study as it allowed our method to detect and map the small wetlands that are characteristic of the prairie pothole landscape. We used a low shape criterion (0), which controls the influence of colour on the segmentation process, as we wanted color to have a strong influence on segmentation. We also used a high compactness criterion (0.8) for more compact image object shapes. Wetlands have been found to be more recognizable in object-based analysis by using low shape criteria and the compactness criterion has been shown to have little effect on the detection of wetlands (Moffett & Gorelick, 2013).

To reduce the probability of classifying roadside ditches as wetlands, we buffered a vector polyline road layer for each of the study sites by 15 m on each side. Fifteen meters was determined to be sufficient as the roadside ditches of most roads were included entirely within this buffer. This 15 m buffer layer was input as a vector layer to constrain the segmentation so that the image objects would not transverse roads and was also input as a binary raster layer, which was used in the classification of image objects.

We established a subset of study sites within the study area to use for calibration and validation of the wetland mapping method using the reference data. To establish study sites, we conducted a two-step cluster analysis on the entire watershed that delineated areas with similar characteristics that affect wetland formation, including moisture deficit (i.e., precipitation minus potential evapotranspiration, P-PET) (Hamon, 1961), geology, topography, and land use/land cover of the watershed. The two-step cluster analysis was used as the data included both continuous and categorical data types. The first step involved pre-clustering to determine if the current record should merge with the previously formed clusters or start a new cluster based on the log-likelihood distance criterion (Bacher *et al.*, 2004). The second step took the results of the first pre-clustering and performed standard hierarchical clustering on the pre-clusters (Bacher *et al.*, 2004).

The two-step cluster analysis automatically delineated two clusters within the watershed (Figure 2.4). There was good cohesion and separation between the two clusters. We randomly selected 64 1.5 km by 1.5 km calibration and 65 1.5 km by 1.5 km validation sites within cluster 1; and 65 1.5 km by 1.5 km calibration and 60 1.5 km by 1.5 km validation study sites within cluster 2 (Figure 2.5). Besides belonging to a given cluster, validation and calibration sites were within the coverage area of the reference data and did not have a large water body that occupied the entire 1.5 km by 1.5 km area. The cluster analysis was done using the Statistical Package for the Social Sciences (SPSS) (SPSS, version 21).

The threshold for the mean p_{dep} value within terrain objects for mapping smaller wetlands (scale parameter = 2) was determined via calibration to the CWI reference data. We

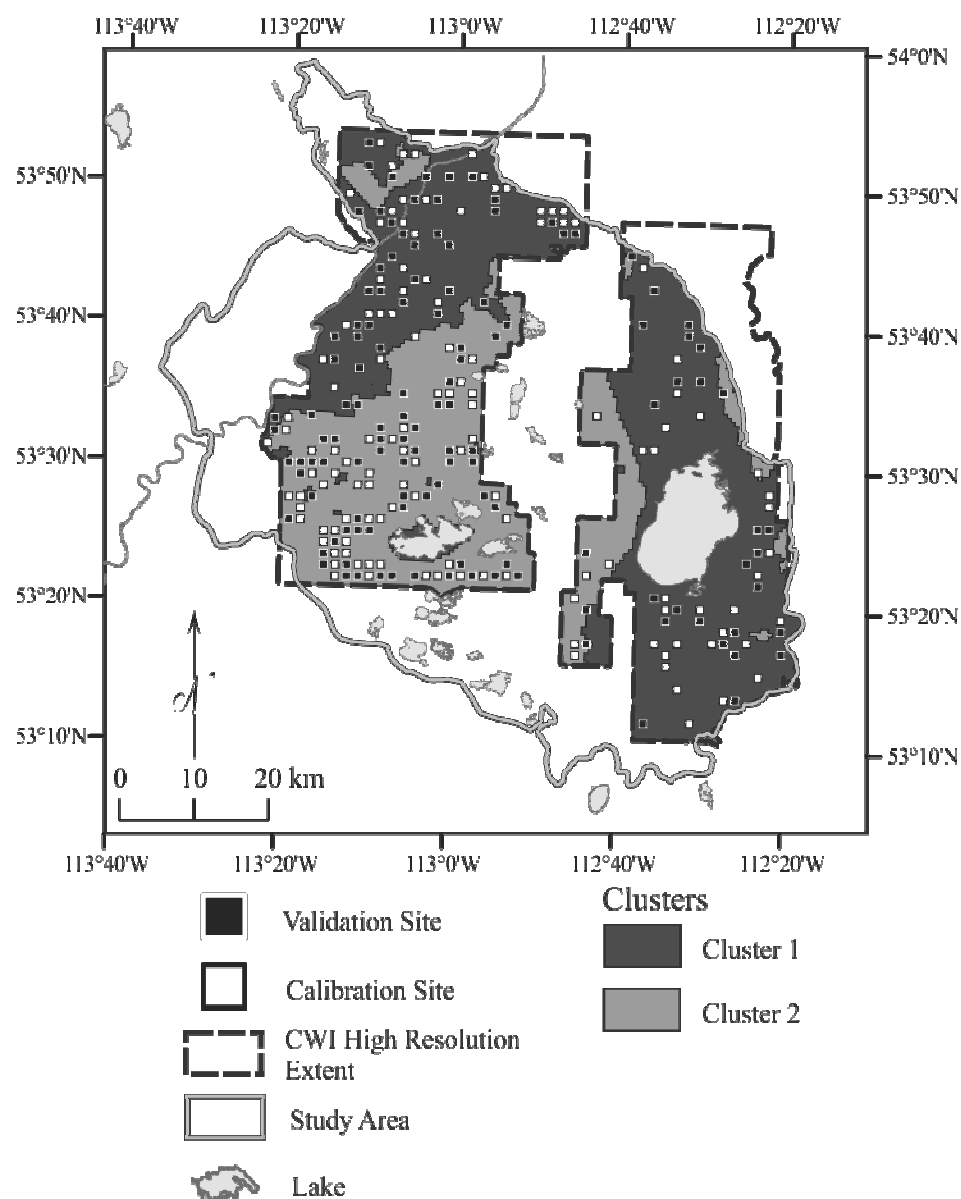


Figure 2.5: Location of the study sites used for calibration and validation of the automated object-based wetland inventory technique using terrain objects within the Beaverhill watershed, Alberta, Canada.

classified the terrain objects of the 125 calibration sites by applying various thresholds of the mean probability of depression values within a terrain object. We applied mean p_{dep} thresholds to the terrain objects at 0.05 intervals ranging from 0.30 to 0.70. The Pearson coefficient (r) and absolute difference in wetland area between the object-based classified wetlands and the reference wetlands (%) were calculated. The threshold was selected to (1) maximize the r between the two images, and (2) minimize the absolute area of the difference in wetland area between the object-based classification and the reference data. A threshold was selected for each study site, then the average threshold for all sites within each cluster was calculated, and finally the average threshold for all clusters was calculated. Any terrain objects with a mean p_{dep} value higher than this threshold were classified as a wetland. The threshold for the mean p_{dep} value in an image segment was determined by visually assessing and comparing the results to the smaller scale parameter to determine if areas of wetlands that were not being classified as wetlands using the smaller scale parameter and threshold were being mapped using the larger scale parameter threshold.

2.2.3 Automatically Delineated Wetlands – Open Water and Wet Meadows

Once the outer boundary of the wetland was delineated, we used a time series of wetland inventories (1962, 1970, 1980, 1992-1993, 1999, and 2009) that were derived from historic aerial photographs to map the open water and wet meadow of the wetlands. The aerial photographs were of varying scales with the lowest scale being 1:31,680 in 1962. The aerial photographs increased in scale over the time period as technologies advanced to 1 meter (m) in 2009. The aerial photographs for 1962 were taken in May and June, for 1970 they were taken in July and August, for 1982 the majority were taken in August and September with September 1981 data used where required, for 1993 the majority were taken in May with July and August 1992 data were used where required, for 1999 the aerial photographs metadata did not include time of capture information, and for 2009 the aerial photographs were taken April and May. The aerial photographs for all years were scanned and re-sampled to 1 m resolution to standardize the aerial photographs for pixel resolution and scale. To create the historic wetland inventories, a different object-based

segmentation method using the multi-resolution segmentation algorithm (Batz & Schäpe, 2000) was applied to the historical aerial photographs. Specifically, the segmentation was conducted using a scale parameter of 40 (rather than 20 and 2 used with the LiDAR analysis), due to the poorer contrast of the aerial photographs and the increased spectral variation that exists in aerial photographs in comparison to LiDAR elevation models. . The scale parameter of 40 was chosen as it was able to capture the small wetlands in one segment and divided the larger wetlands into a reasonable number of segments for classification. Additionally, a scale parameter of 40 is consistent with past studies (e.g., Frohn *et al.*, 2009). Once the aerial photographs were segmented into image objects, the resulting image objects were manually classified to delineate the outer boundary of the wetland. Once the outer wetland boundaries were established, the inside of the boundaries of the wetlands were re-segmented into image objects using a smaller scale parameter of 30. The smaller scale parameter of 30 was chosen to re-segment the interior of the wetland boundaries as, based on visual inspection, this scale parameter effectively delineated the open water and wet meadow zones within wetlands. The image objects within the wetland boundaries were then classified manually as open water and wet meadow based on visual cues from the aerial photograph. This time series of aerial photography captured the majority of the range of natural variability in climate conditions within the Beaverhill watershed over the past 52 years.

A water permanence map was created using overlay analysis of the 6 wetland permanence layers for each year. Areas of the wetland that had water for all 6 of the years were considered to have 100% water permanence as water persists during varying natural climatic conditions. Areas that did not have water during any of the years were given 0% water permanence, not necessarily indicating the absence of water, but that the water may only be in the wetland temporarily. To map the extent of open water within the wetland objects for the object based wetland inventory using terrain objects and derived from LiDAR, we applied a threshold of 100% water permanence to the wetland permanence map. This threshold was deemed appropriate as 2009 was a particularly dry year with low amounts of precipitation. Any portion of the wetland that met the threshold criteria was classified as open water. To delineate wet meadow, we classified

everything that was within the wetland boundary (produced as a result of the small and large scale parameter classification) and surrounding the open water as wet meadow.

2.2.4 Method Testing

We tested the wetland mapping method by using the thresholds established from the 125 calibration sites and applying them to the 125 validation sites. We segmented the probability of depression maps for the 125 validation sites using the previously mentioned segmentation method and classified the image-segmented maps using the mean terrain object thresholds. To form one final wetland inventory, we used the parameters that were established via the calibration process on the validation sites for the watershed. We merged and dissolved the results of both scale parameters to form one final wetland inventory. We removed any polygon features that had an area of less than the minimum mapping unit (MMU) (0.02 ha) in both the reference data and the mapped data.

The MMU is the minimum area of a wetland that can be mapped using a given wetland mapping method. The MMU varies for each individual wetland mapping method and is dependent on the resolution of the input data and the mapping method. The high-resolution Canadian Wetland Inventory, the reference data for this study, had a MMU of 0.02 ha. Minimum mapping units for automated wetland mapping methods tend to be slightly larger due to the coarser resolution of data inputs and the background noise that can be detected during the processing. Reif *et al.* (2009) found that the accuracy of their automated wetland mapping methods increased dramatically when wetland size was > 0.2 ha. The MMU of wetlands mapped using LANDSAT data can be as low as 0.09 ha as this is the resolution of one single pixel, but in practice, it is usually around 1 ha (Grenier *et al.*, 2007). The theoretical minimum resolvable unit of our automated wetland method was 0.0009 ha, due to the 3 m spatial resolution of the LiDAR DEM. We estimated the actual MMU for our automated wetland method to be 0.02 ha, as removing wetlands in both inventories less than 0.02 ha in size decreased the overall omission error (4%) and commission error (2%). Increasing or decreasing the MMU did not result in a substantial decrease in either the omission or commission error (~1%), therefore 0.02 ha was

selected as an appropriate MMU. This MMU is consistent with the reference data and finer than a large majority of current automated wetland mapping methods.

2.2.5 Accuracy Assessment

The accuracy of our method was determined by intersecting the wetlands mapped using our method with the reference data wetlands (Frohn *et al.*, 2009). If a mapped wetland intersected a wetland within the reference dataset, then that wetland was present in both datasets and therefore assumed to be correct. Though this accuracy assessment method does not compare the wetland size or shape, we deemed it to be appropriate as the shape and size of wetlands can be dynamic varying with climatic conditions, and therefore comparing wetland size and shape would likely lead to erroneous accuracy statistics as the inventories were not created at the exact same time using the exact same method and data inputs.

The accuracy of our method was determined by calculating the omission and commission accuracy. The omission accuracy (producer accuracy) was calculated as the number of wetlands in the reference dataset that intersect the object-based mapped dataset divided by the total number of wetlands in the reference dataset. This omission accuracy number was then subtracted from 1 and multiplied by 100 to provide us with percent error. The commission accuracy (user accuracy) was calculated as the number of wetlands in the object-based mapped dataset that intersected the reference dataset divided by the total number of wetlands in the object-based mapped dataset. These commission accuracy numbers were then subtracted from 1 and multiplied by 100 to provide us with the percent error.

2.3 Wetland Loss Estimate

We applied the developed wetland mapping method to the entire Beaverhill watershed to create a wetland inventory that can be used to estimate wetland loss. To estimate the rate of wetland loss, we used the power law wetland area vs. frequency function (Birkett & Mason, 1995; Le & Kumar, 2014; Lehner & Döll, 2004; Miller *et al.*, 2009). The power law wetland area vs. frequency function (Figure 2.6) is based on the premise that water

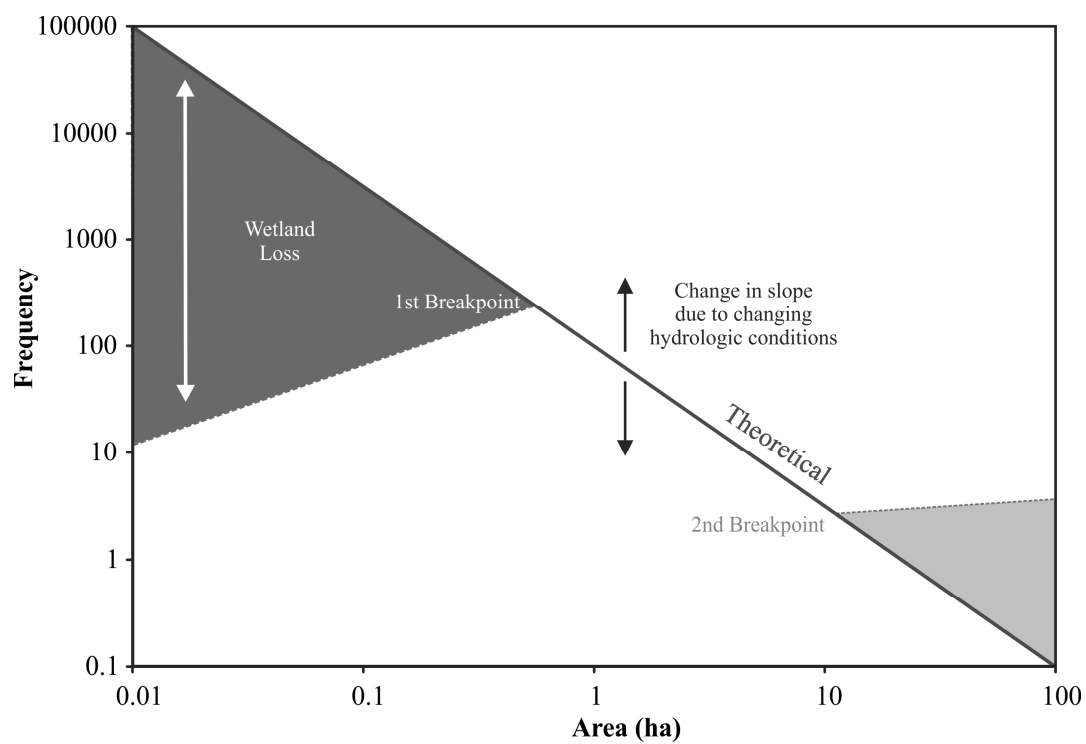


Figure 2.6: Interpretation of the power law wetland area vs. frequency plots.

bodies are fractal, and thus the frequency of the area of water bodies when plotted on logarithmic-logarithmic scales produces a straight line (negative linear relationship) in an undisturbed region (Kent & Wong, 1982).

We established area class sizes (bins) and maximum wetland area and minimum wetland frequency thresholds for the power law wetland area vs. frequency plot (Table 2.2). The bins for wetland area were equal to the resolution of the dataset that was used to create the wetland inventory. Thus, an area wetland class size of 0.0009 ha (9 m²) for the automated object-based wetland inventory using terrain objects was used. We also applied a minimum wetland size threshold to the analysis as extremely small wetland features detected in the inventory are likely to be saturated areas, not functioning wetlands. We ran two separate power law analyses based on two area thresholds: (1) we removed all wetlands less than 0.0036 in size (2 by 2 window of pixels) to reduce the mixed pixel problem; and (2) we removed any wetland less than 0.02 ha in size as this was the estimated MMU of the wetland inventory.

There are often two breakpoints in the power law wetland area vs. frequency function. To determine the wetland area breakpoint, we conducted piecewise linear regression analysis on the wetland area vs. frequency data. The piecewise linear regression grouped wetlands based on different relationships shown in the wetland data (Seber & Lee, 2012). Initially, we used a three segment piecewise linear regression that determined two breakpoints in the wetland data. We used the breakpoint in the larger wetland area classes to remove any bins that were above this breakpoint and to remove the bins that had the same frequency as the bin with the breakpoint. Typically, the larger wetland area breakpoint would occur at a bin with a frequency of 1, so bins with a frequency of 1 were removed from the analysis. Once these data were removed, a two segment piecewise linear regression was conducted on the remaining data to identify the second, smaller wetland area breakpoint from the theoretical. The theoretical is a straight line that was created by extrapolating the power line from the wetland area-frequency points that were above the small wetland area breakpoint and below the large area breakpoint. Since there is a preferential loss of small wetlands in the prairie pothole region (Miller *et al.*, 2009),

Table 2.2: Standardized data parameters for use in the power-law wetland area vs. frequency function with information about how the parameters were selected.

Parameter	LiDAR Inventory	Determination
Bin Size	0.0009 ha	Fixed - based on pixel size of input data
Bin Frequency Removed	Variable	Based on the 2nd breakpoint established using 3 segment piecewise linear regression analysis
Bin Area Removed		

wetland loss was estimated as the difference between the observed break in slope in the small wetland area classes and the “theoretical” power line extrapolated from the area classes above the smaller wetland area breakpoint (Figure 2.6).

Chapter 3: Results

3.1 Wetland Inventory

The final wetland mapping method and a visual example of the outputs and inputs during each step can be found in Figure 3.1. Our wetland mapping procedure mapped 5147 wetlands greater than 0.02 ha with a total area of 2694.49 ha.

3.1.1 Wetland Mapping Threshold Determination

The averaging process to determine a threshold for the smaller scale parameter resulted in a threshold of 0.52; meaning that any image object that has a mean p_{dep} value greater than 52% will be classified as a wetland. The smaller wetland objects were more sensitive to the threshold as there is a smaller sample size of pixels within each image object. Nonetheless, this threshold appeared robust, and similar thresholds have been utilized in other physiographic regions (e.g., Creed *et al.*, 2003). The image objects from the larger scale parameter segmentation were classified as wetlands if the mean p_{dep} value within an image object was greater than 0.45. This threshold was smaller than that of the scale parameter of 2 as the larger scale parameter is able to detect larger wetlands with increased accuracy, thus less uncertainty exists when mapping larger wetlands. The statistics used to determine thresholds in the mean p_{dep} value within terrain objects including the correlation coefficient and the absolute magnitude of the difference in wetland area between the reference data and the results of our wetland mapping for the study sites are shown in Figure 3.2. The difference in size of the image objects between the two scale parameters is presented in Figure 3.1.

3.1.2 Accuracy Assessment

The ability of our mapping procedure to delineate wetlands on the landscape varied in each of the clusters. We were able to map wetlands with omission errors of 17% for Cluster 1 and 21% for Cluster 2; and commission errors of 41% for Cluster 1 and 50% for Cluster 2 (Table 3.1). The overall omission error for all of the study sites in all of the clusters was 18% and the overall commission error was 45%. A map showing an example of the wetland mapping results overlain with the reference data for a study site is

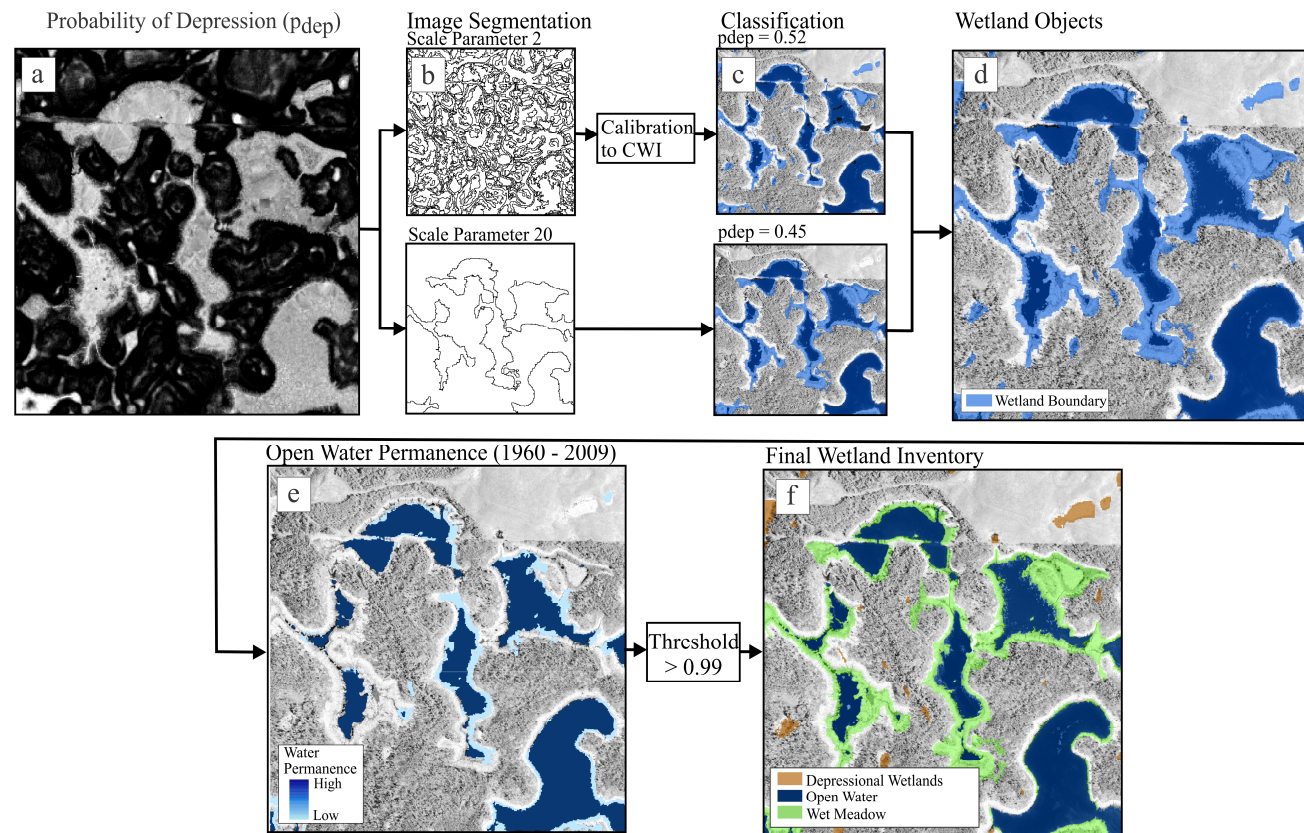


Figure 3.1: Maps showing each step of the object-based wetland delineation technique using terrain objects derived from LiDAR data shown for a 1 km x 1 km area within the Beaverhill watershed: (a) probability of depression (p_{dep}) map; (b) terrain objects produced using the scale parameters 2 and 20; (c) classification of terrain objects using two thresholds, a threshold of 0.52 for the small scale parameter and a threshold of 0.45 for the larger scale parameter; (d) terrain objects classified as wetland using both thresholds; (e) permanence of open water map derived from a time series of object-based wetland inventories using image objects from aerial photography where presence of open water is defined as probability $> 99\%$; and (f) final object-based wetland inventory using terrain objects with open water, surrounding wet meadow, and depressional wetlands delineated.

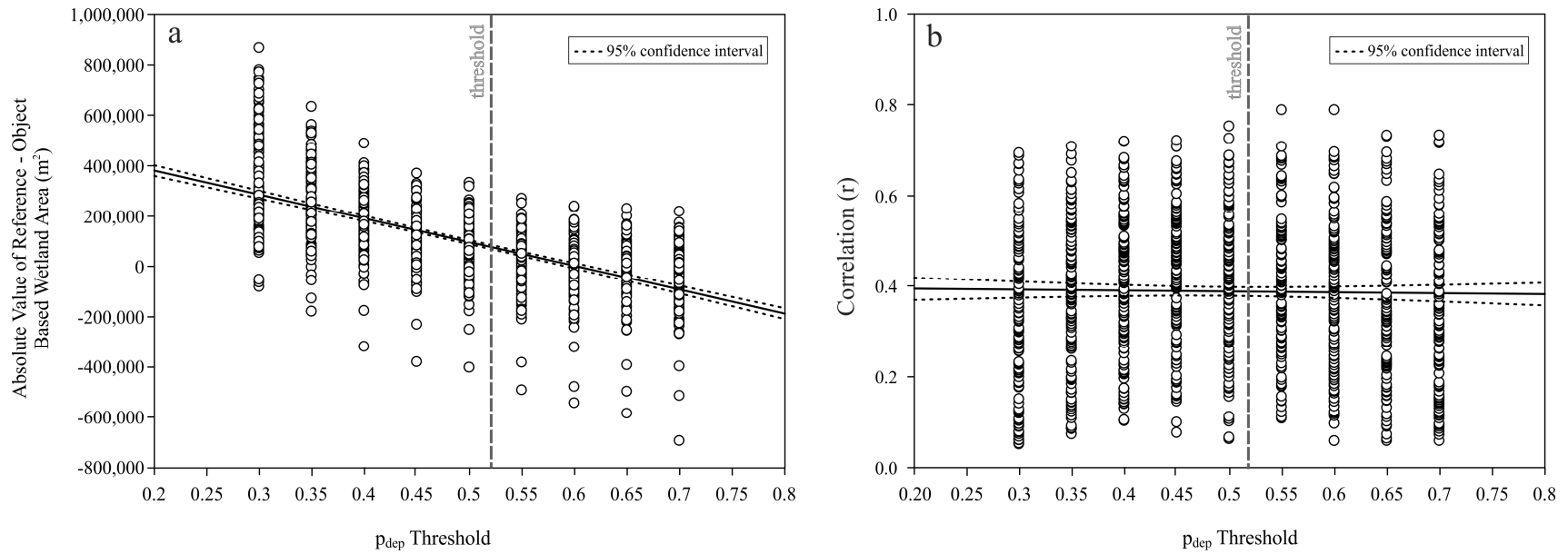


Figure 3.2: Probability of depression (p_{dep}) threshold used to classify terrain objects as wetlands – potential p_{dep} thresholds ranging from 0.3 to 0.7 at 0.05 intervals were tested using 125 calibration sites. We sought to identify the mean terrain object p_{dep} threshold that (a) minimized the absolute value of the difference in area between the object-based wetland areas using terrain objects and the reference wetland, and (b) maximized the correlation of area between the object-based wetland areas using terrain objects and the reference wetlands.

Table 3.1: The omission (producer) and commission (user) errors for each validation site in each cluster for the object-based wetland mapping technique using digital terrain objects. The accuracies were based on intersection of the reference data and the object-based terrain object wetland inventory.

	Cluster Description	Omission Error	Commission Error
Cluster 1 (61 Sites)	Predominantly made up of the moraine, which is a mix of forested and other natural land covers.	17%	41%
Cluster 2 (64 Sites)	Predominantly agricultural regions of the watershed with urban and industrial areas interspersed throughout.	21%	50%
OVERALL ERROR (125 Sites)		18%	45%

shown in Figure 3.3. These results indicated that our method was effective at detecting wetlands on the landscape that were in the reference data; however, the commission error indicated that we detected a large number of objects that were classified wetlands that were not in the reference dataset.

The size of the wetlands that are being committed or omitted tend to be small in size, with a large number of the wetlands being 0 - 0.1 ha in size (Figure 3.4), indicating that the small wetlands were difficult to detect. By applying object-based segmentation to the p_{dep} map, as opposed to applying a straight threshold to the p_{dep} map, decreased our commission error by 5%. Further, by using object-based segmentation to segment the image into two sizes of terrain objects, we were able to decrease the omission error by 4%. Our method was able to detect some hydrological connections between wetlands due to the high-resolution nature of our input LiDAR DEM. This was indicated by individual wetlands in the reference data set that were encompassed by one wetland with corridors in between the individual wetlands in the reference dataset. When an aerial photograph was underlain under the wetland inventory you could see a surface hydrologic connection between these wetlands.

We overlaid the results of our wetland inventory and the reference data onto the water permanence map that was derived from historical aerial photographs to examine the hydroperiod of wetlands that were being detected and over detected by the wetland mapping method (Figure 3.4). Results indicated that our method accurately detected the permanent wetlands with open water. Additionally, this analysis indicated that the overestimation of wetlands tended to predominantly be wetlands that were small in area and temporary, having either saturated soils or only being filled with water during spring melt based on the derived water permanence layer.

3.2 Magnitude of Wetland Loss

When we applied the power law wetland area vs. frequency function to any wetland feature greater than 0.0036 ha (2x2 pixel window) to reduce the mixed pixel problem, a historical wetland number loss of 69.3% and wetland area loss of 9.96% was

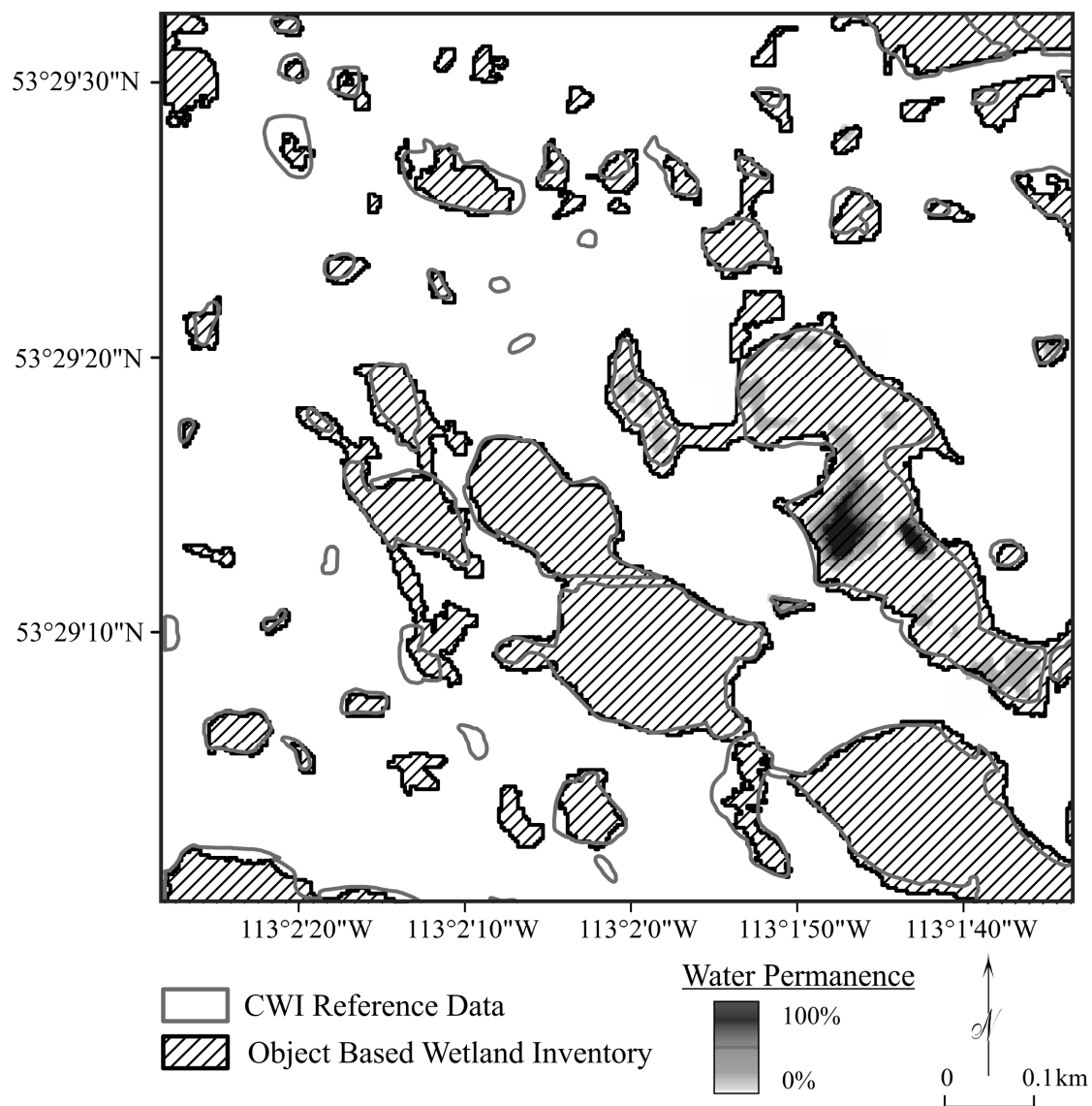


Figure 3.3: Map of object-based wetlands using terrain objects from LiDAR data (black hatching) and the reference wetlands (grey outline) overlain on the permanence of open water map showing that the object-based wetland inventory using terrain objects detected a larger number of small, temporary wetlands within the watershed.

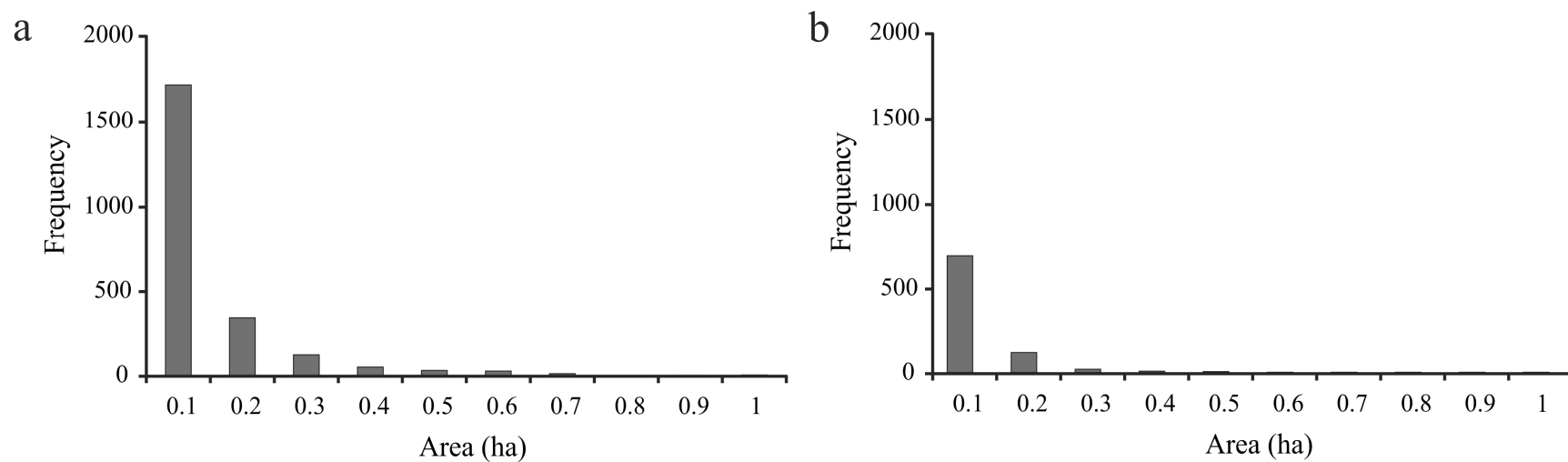


Figure 3.4: Frequency distributions of the area of the (a) committed wetlands and (b) the omitted wetlands from the wetland inventory using terrain objects derived from LiDAR data.

estimated (Figure 3.5). When the power law wetland area vs. frequency function was applied to any wetland feature greater than 0.02 ha in the 2009 terrain objects wetland inventory, we estimated a historical loss (from the beginning of development) of 16.17% number loss and 2.56% area loss (Figure 3.6). The high number loss and lower area loss for both wetland estimates indicates that there has been a preferential loss of small, likely isolated, wetlands within the watershed.

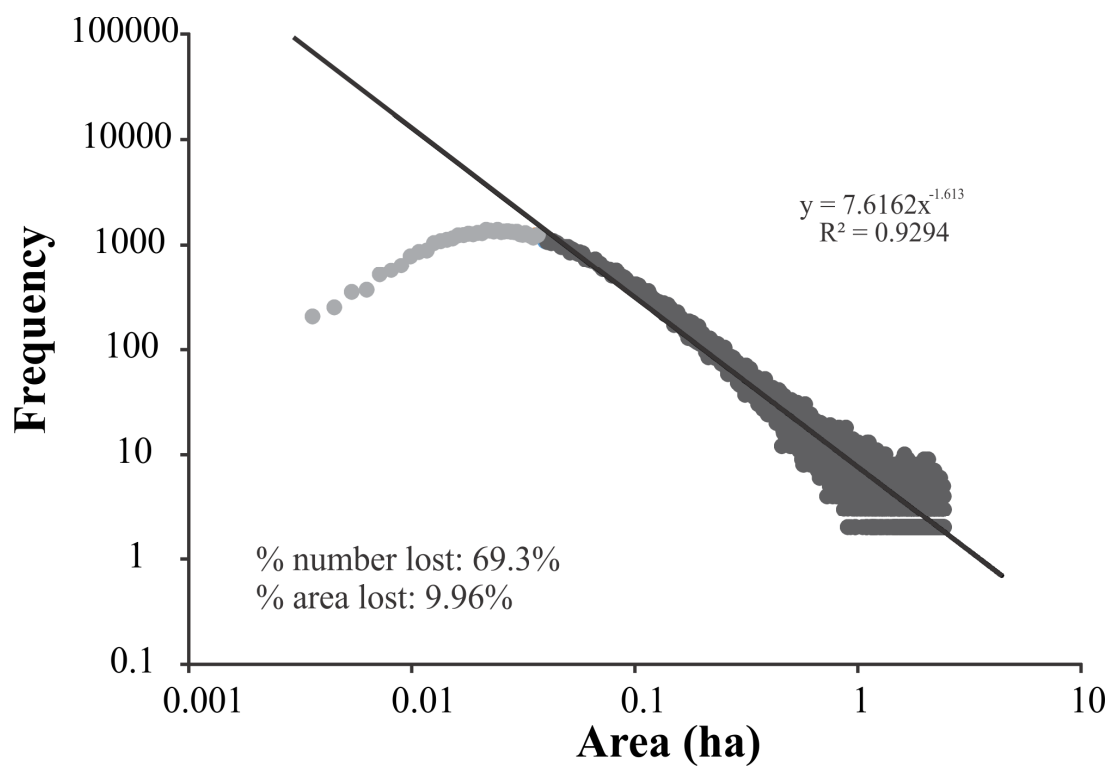


Figure 3.5: The power law area vs. frequency function applied to any wetland object greater than 0.0036 ha in the 2009 LiDAR derived wetland inventory using terrain objects. Within the Beaverhill watershed, historically, there has been an estimated 69.3% number loss and 9.96% area loss of wetlands.

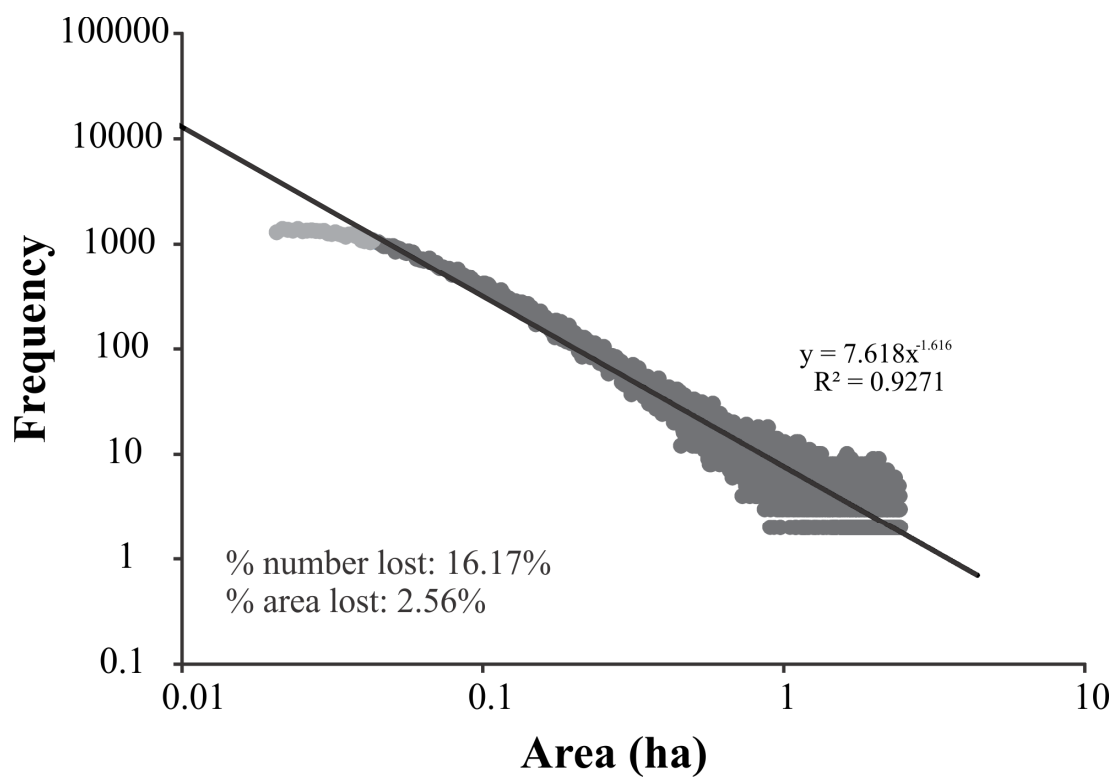


Figure 3.6: The power law area vs. frequency function applied to any wetland object greater than 0.02 ha in the 2009 LiDAR derived wetland inventory using terrain objects. Within the Beaverhill watershed, historically, there has been an estimated 16.17% number loss and 2.56% area loss of wetlands.

Chapter 4: Discussion

4.1 Wetland Mapping

Accurate wetland inventories will assist policy and decision makers to balance economic and development needs while maintaining the important functions and ecosystem services that these wetlands provide. This is critically important as the wetlands that are predominantly developed are the small, temporary wetlands in agricultural fields or those surrounding urban areas. Without knowledge of the location of these wetlands, the concomitant loss of ecosystem services is unknown (Zedler & Kercher, 2005).

We present an automated wetland mapping technique using terrain objects derived from LIDAR DEMs that is effective at mapping wetlands and sensitive to capturing small (< 1 ha) wetlands. The object-based segmentation and classification contributed to the success of our method as it considers not only spectral homogeneity within the object, but the surrounding pixels, and the spatial location of the object (Moffett & Gorelick, 2013). Our method was relatively successful at detecting the presence of wetlands, including the small GIWs within the study area. The ability of LiDAR to detect small changes in topography is critical, as this ability allows LiDAR to effectively detect the depressional wetlands that are characteristic of the PPR (Haas *et al.*, 2009).

The higher number of wetlands detected using our method could be attributed to several factors. First, the automated wetland mapping method may classify background noise as wetlands; this background noise tends to be small in area, especially when using high resolution inputs. To overcome the issue of background noise, we implemented the MMU of 0.02 ha which is consistent with the MMU of the reference data. Even though we implemented this MMU, more wetlands, in comparison to the reference data, were still being detected. Second, the automated wetland mapping method may identify small, ephemeral wetlands that are present but not included in the reference data. The input data layers used to create the high resolution Canadian Wetland Inventory are higher in resolution than most automated

wetland mapping methods, but it is possible that the method may miss some of the smaller, ephemeral wetlands. It has been found that provincial wetland inventories tend to underestimate the presence of wetlands. Gala and Melesse (2012) utilized LANDSAT ETM+ data, RADARSAT SAR data, and a LiDAR DEM to map wet areas in the PPR in Saskatchewan. They compared their results to provincial wetland maps and found that the size and number of wetlands in their wetland inventory were much larger than the provincial inventory. Their results indicate that the small, ephemeral wetlands were primarily being missed when they compared the two inventories (Gala & Melesse, 2012). While the provincial inventory they used for comparison in their study was coarser in resolution than the one used in this study, the results of their study indicate it is possible that we are detecting real wetlands that were not captured in the CWI reference data. However, field verification is required to determine if this is true.

When using aerial photography or other satellite imagery to map wetlands, it is often difficult to delineate the full extent of the individual wetland basin as the vegetation patterns may make establishing the boundary of the wetland difficult in certain types of wetlands (e.g., ephemeral wetlands), and wetland boundaries are extremely dynamic in nature and dependent on the climate of a given year (Maxa & Bolstad, 2009). Further, it is highly dependent on the time of year and the season the remotely sensed images were captured in. One advantage of creating a wetland mapping method based on LiDAR DEM is that the results are not sensitive to climate and time of year to the same degree as aerial photographs and satellite images. However, to achieve the best results, LiDAR should be captured in the driest part of the year, or during dry years to capture the full extent of any depressions as it is unable to penetrate the surface of the water. To map wetlands using aerial photographs or satellite imagery, visual cues, pixel values, or spectral signatures are required, which are highly influenced by the time and date of year they are captured. LiDAR is able to detect depressions and temporary and ephemeral wetlands regardless of whether or not the data was captured during spring melt which is advantageous as the optimal window for LiDAR capture during the year is wider than that of aerial photographs.

A drawback of using aerial or satellite imagery to map wetlands is that it is often difficult to determine if there are wetlands under forest vegetation. This often results in the underestimation or inaccurate delineation of wetlands in forested regions, depending on the time of year that the imagery is captured. Several of the study sites selected for both validation and calibration contained large areas of trees due to the presence of the Cooking Lake Moraine in the center of the watershed. LiDAR is able to overcome the limitation of detecting wetlands underneath vegetation canopies as it has the ability to penetrate through gaps in the canopy of trees in forested areas and detect the underlying topography. Not only can LiDAR develop under canopy DEM models, these DEMs have been found to be quite accurate. Reutebuch *et al.* (2003) found that the vertical accuracy of LiDAR terrain models underneath a primarily conifer forest canopy decreased with increasing canopy cover; however, the decrease in accuracy was extremely small. A similar method described in this paper was conducted in the forested catchment of Turkey Lakes, Ontario and was found to be effective in delineating the boundary of a large wetland covered entirely by the forest canopy (Creed *et al.*, 2003). Due to the increased ability of LiDAR to detect wetlands under forest canopy, our method was able to detect sub-canopy wetlands that other methods, such as using aerial photographs to delineate wetlands, may not be able to detect.

Our method is sensitive to the types of land use that it is applied to. The wetland mapping method is effective at detecting the presence of wetlands in natural and agricultural land types; however, it is less effective in urban and industrialized areas. A potential drawback of our method is that it is unable to distinguish between natural and man-made depressions on the landscape. In urban and industrial areas, the wetland mapping method detects man-made features such as the depressions surrounding industrial tanks, depressions in the middle of several lane highways, and depressions due to grading of the earth's surface or construction. Thus, the application of our method to urban areas should be done cautiously.

Future work will focus on the inclusion of other data sources (e.g., RADARSAT, IKONOS imagery, etc.) to determine if the committed wetlands are present on the

landscape. This will involve conducting a field campaign to further validate (and potentially calibrate) our method. Further, future plans include extending the wetland mapping method to not only identify wetlands but to develop an automated method to classify them according to the Canadian Wetland Inventory (CWI) classes of swamp, marsh, fen, and bog. In addition to the CWI classes, developing a method to classify the wetlands according to the Stewart and Kantrud Classification System of Natural Ponds and Lakes in the Glaciated Prairie Region (Stewart & Kantrud, 1971) would be beneficial as this classification system is widely used in the PPR.

4.2 Wetland Loss Estimate

The ability to estimate wetland loss rates in a standardized manner allows for the evaluation of the extent of wetland loss on the landscape. The effective conservation and protection of wetland ecosystems is critically important as the loss of wetlands in the PPR region of Canada has been cited as a contributing factor to the catastrophic floods that have occurred within this region (Pomeroy *et al.*, 2014).

4.2.1 Power Law

The power law wetland area vs. frequency function is an effective method that can be used to estimate wetland loss rates. One particular benefit of using the power law to estimate wetland loss is that it requires only a wetland inventory as input to conduct the analysis, no field work or time consuming modelling. Further, the method is standardized as many of the current wetland loss rate estimates are derived using various methodologies, with differing definitions of what constitutes wetland loss (Dahl & Watmough, 2007). However, to detect the break in slope in the small wetland area, high-resolution data wetland inventories are required, as wetland inventories that mapped wetlands > 0.1 ha have been found to not detect the break in the small wetland area classes (McDonald *et al.*, 2012).

4.2.2 Sensitivity of Power Law to Plot Parameters

The power law wetland area vs. frequency function is sensitive to the selection of the area bin class size and the area and minimum frequency criteria used to generate the

function. Increasing the area bin class size tends to result in an increase in both % area and % number loss due to the increase in frequency observed in the area classes that break from the slope. Having the area class equal to the pixel size of the input data used to create the wetland inventory allows for more accurate wetland area loss estimates as a wetland object within the inventory can only increase in area by the size of the pixel. Establishing a lower wetland area threshold also affects estimates, as removing wetlands in the small wetland area classes reduces wetland loss estimates. To our knowledge, there are no existing studies that test the area class bin sizes and area and frequency selection effects.

In addition to area class size, the power law wetland area vs. frequency function is also sensitive to the number of wetlands within a wetland inventory. The approach should not be used for small geographic areas with a small sample size of wetlands as this often does not provide a high enough frequency in the area classes to form a robust power law. For this reason, it is recommended that at a minimum, this analysis be done at a regional watershed scale.

4.2.3 Comparing Power Law Function Wetland Loss Estimates to other Approaches

The accuracy of our estimated loss rates can be validated through comparison to the limited existing estimates for the region. Environment Canada has estimated wetland loss in the Prairie Pothole Region of Canada by estimating wetland loss along a series of transects. However, it is important to note that the transects surround the Beaverhill watershed – none of them are contained within the watershed boundary. Watmough (2011) estimated cumulative wetland loss by identifying evidence of drained or lost wetlands at 1985 baseline in combination with recent lost area. These researchers used a combination of aerial photograph analyses and field verification to delineate wetlands and identify any sign of anthropogenic disturbances. This approach to monitoring wetland losses is time consuming and requires data that typically does not exist at high enough resolution over large geographic areas, and therefore cannot be used to obtain estimates of wetland loss across the entire Prairie Pothole Region.

The results of their study calculated a mean cumulative wetland area loss of 14.35% along the transects (range: 1.57% - 53.17% per transect). This 14.35% average area loss is close to the 9.96% historic area loss that we are estimating for the Beaverhill watershed in the analysis where we are accounting for the mixed pixels. In the MMU power law analysis (removing 0.02 ha), the estimate of area loss is towards the lower end of the range of loss estimates. Results also found that the average size of wetlands that were considered lost along the transects were 0.20 ha in size (Watmough & Schmoll, 2007), corroborating the preferential loss of small wetlands within the PPR.

Several studies cite large, general wetland loss rates for the developed areas of Canada (e.g., Austen & Hanson, 2007; Bedford, 1999; Tiner Jr, 1984). For example, Warner and Asada (2005) estimate that up to 70% of wetlands have been lost or degraded in the developed areas of Canada since European settlement. Our power law analysis that accounts for the mixed pixels produces a wetland number loss estimate of 69.3%, matches almost exactly to the Warner & Asada (2005) estimate. The power law analysis which removes any wetland less than the MMU found a much lower wetland area loss, which could be partially attributed a large part of the Beaverhill watershed being designated as parks or protected areas (Clare & Creed, 2013).

Chapter 5: Conclusions

5.1 Research Findings

The Prairie Pothole region of North America contains millions of small depressional wetlands that are geographically isolated from larger surface hydrologic networks. These important ecosystems are being disrupted due to urban expansion, agricultural development, and natural resource extraction. Improved estimates of wetland loss are important as it can contribute to an increase in flooding and the development of harmful algal blooms in downstream waters.

The objectives of this thesis were to: (1) develop a novel method for mapping wetlands that is sensitive to mapping the small (< 1 ha) GIWs that dominate the Prairie Pothole landscape; and (2) determine the historic loss (or gain) of wetland number and area for the Beaverhill watershed using the LiDAR-derived wetland inventory created in the first objective.

We developed a wetland mapping method using high-resolution (3 m) LiDAR digital terrain models and object-based segmentation to delineate wetlands in a regional watershed in Alberta. We validated the results to the high-resolution manually derived CWI wetland inventory for the watershed. The results indicated that the wetland mapping method was successful at detecting the presence of wetlands that were in the reference data. The wetland mapping method also detected a number of wetlands that were not in the reference data. The wetlands that were not detected in the reference data tended to be small in area and temporary, indicating that they were likely GIWs. This wetland mapping method was particularly sensitive to the detection of man-made depressions making it an excellent technique for identifying wetlands in natural and agricultural regions. The minimum mapping unit of this wetland mapping method was estimated to be 0.02 ha, as a decrease in accuracy statistics was observed when including wetlands below this threshold.

The results indicated that the wetland mapping method creates a comprehensive wetland inventory. The 2009 object based wetland inventory using terrain objects

mapped ~130,000 wetlands. These results indicate that using LiDAR data, in combination with object-based segmentation, can be a promising approach to mapping wetlands and detecting the abundance and distribution of small wetlands and GIWs in the PPR.

The object-based wetland inventory produced an improved wetland inventory that will lead to better management of wetlands. Small (< 1 ha) isolated wetlands are vulnerable to continued loss on prairie landscapes, in part because they are often not included in wetland inventories. The object-based wetland mapping method captured wetlands by combining object-based classification techniques with high-resolution LiDAR digital elevation models. This method was sensitive to the detection of small, isolated wetlands even in areas of low relief such as the prairie pothole landscape. The improved wetland inventories will allow managers to monitor changes in the spatial and temporal distribution of wetlands and to develop policies to reduce the vulnerability of these wetlands to further loss.

When we used this wetland inventory to estimate wetland loss, we estimated a 69.3% number and 9.96% area loss within the Beaverhill watershed when accounting for the mixed pixel problem. When we removed any wetland less than the MMU (0.02 ha) from the analysis, we estimated a 16.17% number loss and a 2.56% area loss. The difference in loss estimates indicates that to obtain accurate wetland loss estimates, wetland inventories that capture small wetlands are required.

5.2 Research Significance

This research has contributed both technical and scientific knowledge to the scientific community and provides important information to decision makers about wetland loss and mapping. Technically, this research provides a novel method to map wetlands that is sensitive to the detection of geographically isolated wetlands by applying object-based segmentation to the probability of depression layer. Wetland inventories created using this method will be able to provide information on the distribution, density, and location of wetlands on the landscape. The resulting wetland inventory will also provide information about the internal structure and morphometry of the

wetland, including the open water and wet meadow areas. This information is useful to provide insight into the ability of a wetland to provide functions and ecosystem services (e.g., the ability of a wetland to process and retain nitrogen and phosphorus).

The power law area vs. frequency function can be used on existing wetland inventories to assist governments and policy makers to calculate wetland loss in areas of interest. This information can then be used to target conservation to areas that have experienced a large amount of wetland loss. The power law area vs. frequency function also provides a tool that can be used to monitor wetland loss (or gain) over time using historic wetland inventories.

5.3 Future Research Directions

Future research into developing methods to effectively map GIWs needs to be conducted to determine potential ways the method developed can be improved. This work will include field verifying the wetlands that were captured using the wetland mapping method to ensure their presence on the landscape. Additionally, testing the use of other remotely sensed imagery inputs such as high-resolution multispectral imagery (e.g., IKONOS) to further help delineate wetlands will need to be conducted.

There is an associated loss of ecosystem services with wetland loss (McLaughlin & Cohen, 2013; Mitsch & Gosselink, 2000; Zedler *et al.*, 2005). Future work using the power law wetland area vs. frequency function will focus on determining the functional loss associated with wetland loss. This information will be beneficial for use in policy development, to protect these important wetland ecosystems. In particular, the information can be used to inform policy, such as the Government of Alberta's recently implemented wetland policy, which shifts the focus from wetland area to wetland function. The Government of Alberta wetland policy uses both remote (e.g., GIS and remotely sensed data) and field-based relative wetland function assessment tools to assess the value of a wetland for flood reduction, biodiversity, water quality improvement, and human value. The relative wetland function assessment tools use a suite of indicators that were developed based on ecological and hydrological processes from scientific literature. These indicators are then combined

to provide a function score for each wetland function group (i.e., water quality improvement) and an overall function score that incorporates all function groupings for each wetland. Using these tools, the policy strives to ensure that wetlands of highest value are protected along with making sure benefits are conserved and possibly restored in areas where a high amount of wetland loss has occurred.

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Appendix A: Cluster Analysis Study Site Selection

For the Two Step Cluster Analysis conducted in SPSS for the paper we originally specified the number of clusters to be five as we thought that there were approximately five different regions of the watershed. However, the clusters produced as a result of this analysis had poor separation. To remedy this, we had the algorithm choose the optimal number of clusters, which turned out to be two. The results of the five cluster analysis and the validation and calibration sites within those clusters is shown in Figure A.1. We ran the analysis on the calibration and validation sites within five clusters to examine which clusters have better results than others to examine trends or patterns (Table A.1). The results indicate that Cluster 1, which only has 5 sites within it, has a high omission error likely due to the urban land use within the cluster and the inability of the method to distinguish between man-made and natural depressional features.

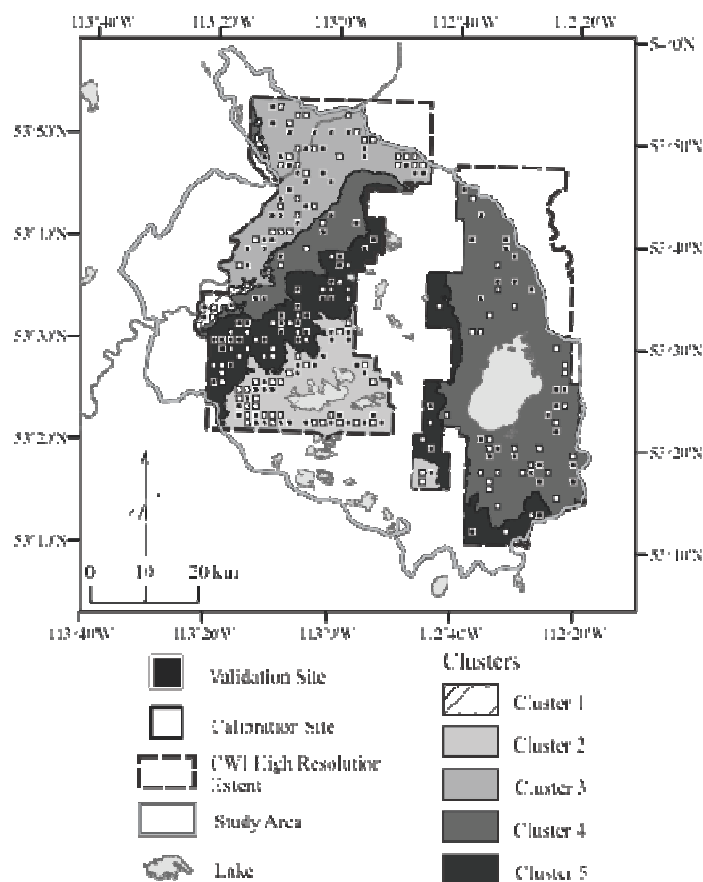


Figure A.1: Map of the five clusters and the location of the study sites within these clusters used for calibration and validation.

Table A.1: The omission and commission error results for the five-cluster analysis for the Beaverhill watershed.

	Description	Omission Error	Commission Error
Cluster 1	Urban land use	20.9%	72.3%
Cluster 2	Southern portion of the moraine, predominantly natural cover.	24.3%	37.8%
Cluster 3	Predominantly agricultural with industrial areas interspersed throughout.	11.7%	57.6%
Cluster 4	Predominantly agricultural and urban land use	19.2%	34.5%
Cluster 5	Northern portion of the moraine, predominantly natural cover	13.6%	46.4%
OVERALL		18.6%	44.9%

Appendix B: eCognition Rule Sets for Wetland Mapping

Scale Parameter 2: Settings

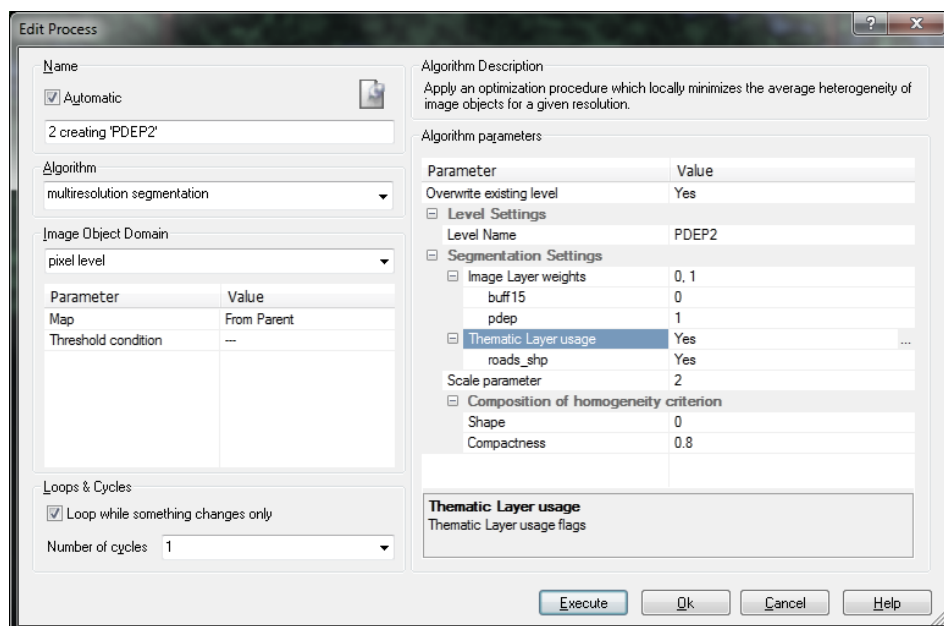


Figure B.1: Segmentation parameters for the scale parameter of 2.

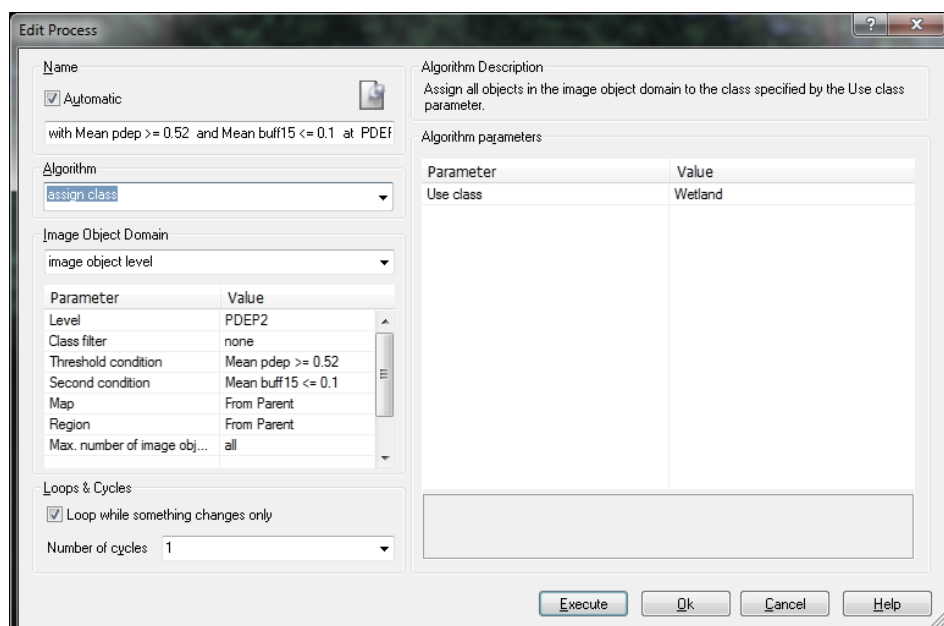


Figure B.2: Classification parameters of the small scale parameter image objects.

Scale Parameter 20: Settings

Edit Process

Name

☐ Automatic

20 creating 'PDEP20'

Algorithm

multiresolution segmentation

Image Object Domain

pixel level

Parameter	Value
Map	From Parent
Threshold condition	---

Loops & Cycles

☒ Loop while something changes only

Number of cycles: 1

Algorithm Description

Apply an optimization procedure which locally minimizes the average heterogeneity of image objects for a given resolution.

Algorithm parameters

Parameter	Value
Overwrite existing level	Yes
<input type="checkbox"/> Level Settings	
Level Name	PDEP20
<input type="checkbox"/> Segmentation Settings	
<input type="checkbox"/> Image Layer weights	0, 1
buff15	0
pdep	1
<input type="checkbox"/> Thematic Layer usage	Yes
roads_shp	Yes
Scale parameter	20
<input type="checkbox"/> Composition of homogeneity criterion	
Shape	0
Compactness	0.8

Scale parameter

Scale parameter

Execute Ok Cancel Help

Figure B.3: Segmentation parameters for the scale parameter of 20.

Edit Process

Name

☐ Automatic

with Mean pdep >= 0.45 and Mean buff15 <= 0.1 at PDEP20

Algorithm

assign class

Image Object Domain

image object level

Parameter	Value
Level	PDEP2
Class filter	none
Threshold condition	Mean pdep >= 0.45
Second condition	Mean buff15 <= 0.1
Map	From Parent
Region	From Parent
Max. number of image obj...	all

Loops & Cycles

☒ Loop while something changes only

Number of cycles: 1

Algorithm Description

Assign all objects in the image object domain to the class specified by the Use class parameter.

Algorithm parameters

Parameter	Value
Use class	Wetland

Execute Ok Cancel Help

Figure B.4: Classification parameters of the large scale parameter image objects.

Curriculum Vitae

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Western Graduate Research Scholarship
2012-2014
Faculty Environment Work Term Report Award
2011
University of Waterloo Geography Entrance Scholarship
2007

Related Work Experience: **Research Technician** - Western University Canada
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Graduate Teaching Assistant - Western University
2012-2014
Research Assistant – Western University Canada
May 2012 – August 2012
Research Assistant - International Joint Commission Great Lakes Regional Office
2011
Student GIS Technician - Town of Amherstburg, Ontario
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2008-2010

Presentations:

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